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SHOULD BEDROOM DOORS BE OPEN OR CLOSED WHILE PEOPLE ARE SLEEPING?

A Probabilistic Risk Assessment

BY

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Abstract

Traditionally the New Zealand Fire Service has been giving the advice to the New Zealand public that it is safer to sleep with their bedroom doors closed. The advice given is not backed up by any technical evidence that it is the best way to position your bedroom door when asleep. Sleeping with your bedroom door closed reduces smoke migration into the bedroom. With the increased use of simple, cheap smoke alarms in many residential houses, it is important to investigate if this is the safest way to position your door when asleep.

The aim of this research is to determine whether it is safer to sleep with bedroom doors open or closed in the event of a fire by performing a probabilistic risk assessment. The recommendation made by this research can be used by Fire Services to give the best advice on whether it is safer to sleep with bedroom doors open or closed. The analysis is carried out using two methods. Firstly by evaluating the expected risk to life to occupants by using FiRECAM (Fire Risk Evaluation and Cost Assessment Model), which is being developed at the National Research Council of Canada. The second method used determines the probability of failure using an event tree method.

Both analyses recommend that it is safer to sleep with bedroom doors closed while sleeping. Although they agree with each other there are many issues requiring further investigation in both analyses. The results of the analyses are only comparable in a relative sense and are not yet able to be compared in absolute terms.

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1.1 Aim and Applicability of Research

Domestic fire fatalities are an increasing problem in New Zealand. To counter this an increased use of smoke alarms in the community has helped reduce the number of fire fatalities, but still, people are dying unnecessarily in fires.

The aim of this research is to determine whether it is safer to sleep with bedroom doors open or closed in the event of a fire. This is determined by a probabilistic risk assessment evaluating either the expected risk to life to occupants by using FiRECAM (Fire Risk Evaluation and Cost Assessment Model) or determining the probability of failure using an event tree method.

The findings of the research will be used to give correct and safe advice to the New Zealand public which, in turn, will help reduce the number of unnecessary domestic fire fatalities. The recommendation to keep bedroom doors closed while sleeping found in this research report can be used by the New Zealand Fire Service in their publicity campaigns to increase public awareness of fire and to create safer houses and therefore communities. Although people may not take heed of the advice because of personal reasons such as children, pets or privacy, it is important that the correct advice of doors open or closed is given.

1.2 Background

Traditionally the New Zealand Fire Service has been giving the advice to the New Zealand public that it is safer to sleep with their bedroom doors closed (Joe Hefford, NZFS, *pers.comm.*). The advice given is not backed up by any technical evidence that it is the best way to position your bedroom door when asleep. With the increased use of smoke alarms in many residential houses, it is prudent to investigate this advice as closed bedroom doors may impair the efficiency of the smoke alarms. Smoke alarms, which help warn occupants of a fire by sounding an alarm when they sense smoke are generally installed outside bedrooms. The New Zealand Fire Service advice may be flawed for two reasons. Firstly if a bedroom door is closed, the smoke produced by the fire may not reach the smoke alarm, and secondly the occupants may not hear the alarm behind the door if they are in a deep sleep. Alternatively, if the bedroom door is closed the risk of fire spread is reduced.

Seventy percent of fatalities due to fires occur in residential dwellings. Smoke inhalation is the leading cause of these fatalities. Carbon monoxide in smoke combined with the lack of oxygen either kills the victim, or renders the victim unconscious thus preventing escape. Generally, smoke inhalation incapacitates occupants before the actual fire affects them. This particularly applies to people asleep and remote from the source of the fire (Irwin 1997). Therefore, well maintained, correctly positioned and reliable smoke alarms are needed in residential dwellings to warn people of a fire. Smoke alarms are relatively cheap and simple to install, they provide an early warning of a fire, assisting occupants to escape from the building or fight the fire.

New Zealand Fire Service statistics show that over 41 percent of all deaths in structures occurred to victims who had been sleeping at the time of the incident (BIA 1998). Fire fatalities usually have one simple feature in common. A serious delay occurred in the occupants of the building becoming, or being made, aware of the fire (Sime 1986). If a smoke alarm is installed and maintained correctly and the bedroom door is positioned correctly then the number of fatalities in domestic fires may be reduced. The New Zealand Fire Service attends approximately 22, 100 fire incidents[1] per year, one fifth of these occur in domestic structures. The average number of fatalities per year for all fires is 32. The majority of these fatalities arise from domestic fires (Irwin 1997)

Socio-economic factors influence the probability of fire and also the use of smoke alarms in private dwellings. Often high risk groups such as those on low incomes or the elderly are less likely to have smoke alarms installed in their houses.

[1] A fire incident occurs every time the fire service responds to an alarm. The incident may be a fire, smoke scare, rescue, false alarm, or hazardous material situation.

1.3 Risk Assessment

A probabilistic risk assessment is performed to investigate whether it is safer for occupants of residential houses to leave their bedroom doors open or closed when they are sleeping. A probabilistic risk assessment is the process of identifying events that may endanger life safety, estimating the frequency at which these events occur and determining the consequence of those events. Probabilistic models are used instead of deterministic models because deterministic models do not necessarily model the most probable fire. Deterministic models use implicit values to get a result whereas probabilistic models use probabilities to calculate the probability of failure and the consequence of that failure to define a hazard.

The analysis in this study is performed in two ways to ensure that the recommendations made by the two methods are the same. The first method is by using an event tree analysis where probabilities of events occurring are combined to determine the probability of failure. The probability of failure is the probability that people do not evacuate from their residence before untenable conditions occur in the event of a fire.

The second method of risk assessment is using the fire risk assessment program FiRECAM (Fire Risk Evaluation and Cost Assessment Model) developed at the National Research Council of Canada. This program determines the risk to life and the fire cost expectation of fire scenarios in a user defined building depending on the fire safety systems installed. The fire cost expectation part of the program is not used as the fire cost is not an important parameter in this study because life safety is considered the main aim. Thus the expected risk to life is the main parameter that this study is aiming to find.

The probabilities of failure defined in the event tree method for an open or closed door situation can be compared. Comparisons are also possible from the expected risk to life values calculated by FiRECAM. A recommendation on whether doors should be left open or closed while sleeping can then be made from the results of these comparisons.

1.4 Scenarios

Scenarios are derived in the probabilistic risk assessment that describe the type of building, occupant characteristics and types of fires to be studied. Occupants can have their bedroom doors open or closed. The scenarios used for both methods of the risk assessment are relatively the same. A single storey house was modelled with only one smoke alarm placed either in the room or outside the corridor of the three bedrooms. The fire origin was in either the bedroom or living area. The type of fires able to be modelled were different for both the event tree method and for FiRECAM, they are as follows:

- A smouldering or flaming fire (event tree method)
- A smouldering, pre-flashover[2] or post-flashover fire (FiRECAM)

The time that the fire starts is at night therefore the occupants are assumed asleep. It is also assumed that the occupants are healthy and are not under the influence of alcohol, drugs or any other sleep altering substances.

1.5 Typical New Zealand House

A typical New Zealand house was determined by discussion with various people involved in the New Zealand residential housing industry. Housing New Zealand, Initial Homes and Peter Ray Homes were consulted and the following basic house was determined:

A three bedroom dwelling with bedrooms at one end of the house and living area and kitchen area at the other end. Room sizes vary between the three companies so an average size was used. It is constructed of timber framing with a brick or wooden exterior.

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[2] Flashover is generally defined as the transition from a growing fire to a fully developed fire in which all combustible items in the compartment are involved in fire (SFPE 1995).

The age range of houses surveyed varied between state houses built in the 1950's to houses presently being constructed. The expected design life of the building is 75 years and the age of the building is ten years.

FiRECAM uses a simplified rectangular outline for the house. For further FiRECAM inputs Section 4.3.1 details what basic building elements were used. Shown below are the typical houses used in the event tree modelling 1.1a and FiRECAM modelling 1.1b. The FiRECAM house is different from the event tree house because of the way that FiRECAM sets up its model. It is only possible to have a simple outline and specify the number of compartments the area is to be divided into. Room sizes can not be specified.

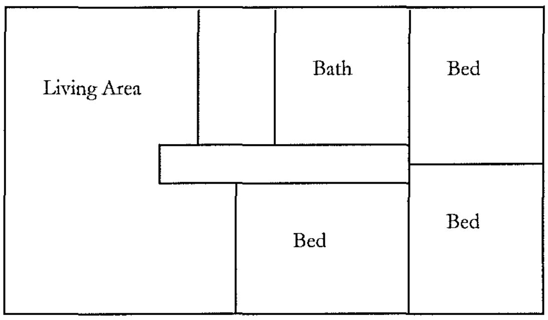


Figure 1.1a Event Tree House

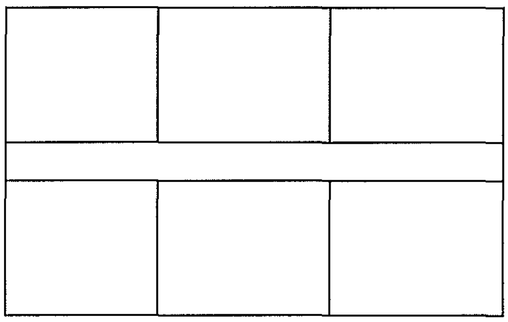


Figure 1.1b FiRECAM House

The door between the hallway and the bedroom can either be open or closed. There is no door between the living area and the hallway, it is considered that the two areas are open to each other.

1.6 Fires Modelled

Fires behave differently in terms of fire growth and smoke spread. Therefore smoke alarms and humans will also behave differently depending on the type of fire modelled. The type of fire modelled in the event tree and FiRECAM analysis can be either smouldering or flaming.

Distinction was made between smouldering and flaming fires because there is a need to recognise the fact that fire growth and smoke spread (which is the principal cause of death) do not develop in the same way for all fires (NFPA 1997).

In the event tree assessment only flaming and smouldering fires are modelled, not pre- or post- flashover fires. This is because this research is concerned with life safety and not fire related costs therefore the time of alerting occupants and the time for evacuating the building is most important. The time frame for smoke alarm activation and evacuation occurs before most fires would develop into a flashover stage.

FiRECAM differs from the event tree analysis as it models smouldering and both pre-flashover and post-flashover fires. The expert data files in FiRECAM give the percentage of fires that are smouldering, pre-flashover and post-flashover.

Smouldering fires can often generate sufficient smoke to be readily detected and the fire can subsequently be suppressed before damage or death occurs. However smouldering fires are also capable of generating smoke that is not sufficiently hot enough to rise and activate smoke alarms and consequently can become fatal (Loveridge 1998). Smouldering fires may be more dangerous to life than a flaming fire due to the smoke and toxic gases involved and that they may not generate sufficient heat to activate sprinklers or heat detectors (Buchanan 1994). There is no substantive information on fire incidents where fatalities have resulted from smouldering fires. This could possibly be due to the fact that smouldering fires may develop into flaming fires after a death has occurred and before the fire is discovered. It is likely that smouldering fires are only a threat when occupants require assistance evacuating to escape the effects of the fire eg. the very young, elderly or mobility restricted (Loveridge 1998).

Quintere *et. al.*(1982) reviewed literature on compartmentalised smouldering fire experiments in order to assemble temperature and concentration data. This data was expanded by experiments at the National Bureau of Standards in the United States of America, which aimed to guide and verify the development of a mathematical model. From these smouldering fire room experiments, hazards from smouldering fires were determined. They determined that a room with a smouldering fire and the effects of elevated temperature, low oxygen and high carbon dioxide levels were not a significant threat to life. However they determined that carbon monoxide could reach hazardous levels in the time range from 50 to 150 minutes. It is expected that if smoke is able to get to a smoke alarm through open doors then it will activate before hazardous conditions occur.

Chapter 2 Literature Review

2.1 Recommended Practise

The New Zealand Fire Service presently recommends the New Zealand public keep bedroom doors closed when sleeping. The reasoning behind this recommendation is that closed doors will reduce fire spread between rooms. With the increased use of smoke alarms in residential houses this advice may not be correct. Although a closed door will prevent fire spread it also blocks approximately 15 dBA of the sound a smoke alarm produces (Smith 1992). A typical smoke alarm emits a sound level of 85 dBA, behind a closed bedroom door the sound heard might only be 70 dBA, which at the pillow level may not be loud enough to wake a heavy sleeper.

Collier (BRANZ 1998) recommends that doors be kept open so that sleepers are able to hear a smoke alarm or to locate the alarm inside the bedroom with the door closed. This recommendation is based on research by "Bukowski" (in Collier 1998) where fires in closed bedrooms resulted in lethal conditions occurring in the bedrooms before smoke alarms located outside the bedrooms responded.

Other recommendations suggest that the bedroom door should be closed. These recommendations come from various sources such as overseas fire service pamphlets, Internet browsing and publicity material by alarm manufacturers. This suggestion almost always comes with the comment that occupants must be sure that the smoke alarm can still be heard with the bedroom door closed. Most of these authorities also comment that the ideal number and positioning of smoke alarms is to have one in every bedroom, and one outside the bedrooms.

A study of 141 adults over 18 years of age in Christchurch (Rusbridge 1999) determined that 78% of people slept with their doors open and 22% slept with their doors closed. The reasons given for given for keeping their doors open or closed were:

- Habit or preference (27%)
- Children and pets (20.5%)

- Fresh Air and Space (20%)
- Security and Privacy (17%)
- Other (11%)
- Fire Security (4%)

From these results it is clear people are not following, or are not aware of, the recommendations made by the New Zealand Fire Service to keep their doors closed. Fire security features last in the list of reasons why people leave their doors open or closed. Of the four percent of people who answered 'fire security', two left their doors open and four left their doors closed. One of the two who left their door open explained they did that for early detection of a fire.

2.2 Human Behaviour

Human behaviour during fire incidents is an important factor determining whether people escape from fires or not. In the past, prevention of fire fatalities has been dealt with solely as a problem of engineering. However, it has become increasingly important to consider psychological and social aspects of fires on people.

Peoples behaviour in a fire is dependent on many factors, these include; the occupants involved, the type of dwelling and a person's familiarity to it, peoples perception of the risk and seriousness of the fire, the stage of development of the fire and the physical cues received (Canter 1990). In most cases, people behave adaptively, in other words, every action taken by the occupant serves a purpose. Adaptive behaviour can be defined as, performing positive actions to lessen the risk of the fire to the occupants and the building. One such example of adaptive behaviour is altruistic behaviour. Altruistic behaviour involves people helping others in selfless actions without any thought to their own safety. It is only possible to help others if people are notified of the fire early enough. Notification of a fire is only possible if a positive cue of a fire incident is received, such as a smoke alarm activating.

As mentioned earlier, human behaviour is partly dependent on the type of occupancy in which the fire occurs (Canter 1990). In almost all residential fire situations it is likely that the primary group will be involved. The primary group is a close knit group of people such as a family. People behave differently when the primary group is involved because they care deeply about what will happen to their loved ones. This is different from office occupancies where it is likely that the primary group is not involved in the fire incident. Human behaviour, when the primary group is involved, is more concerned with making sure other occupants are aware of the fire and then beginning evacuation of the residence. The behaviour is adaptive, all actions that are taken, are believed by the occupants, to be helping their cause (Canter 1990).

Peoples' behaviour in domestic fires has been researched by Canter (1990), the typical behaviour of occupants is adaptive as shown here. The typical sequence of events taken during a fire in the home is as follows (Canter 1990):

1. In the early stages of a fire people notice cues but find them ambiguous and misinterpret or ignore them. If the cue persists, investigation occurs to find the source. The actions vary if smoke or fire is encountered first. Both males and females tend to misinterpret ambiguous cues, though males are more likely to do so and delay investigation. The response of a female may be delayed by interaction with a male, but eventually one of them initiates investigation.

2. When cues are being investigated smoke is likely to be encountered, either in the room of origin or outside it. The occupant is likely to enter the room of fire origin.

3. If a direct encounter with smoke or fire occurs, peoples' behaviour depends on the stage of fire growth, the location of the fire and the time of the event. The differences in behaviour are dependent on whether the investigator is male or female, or if they are occupants or neighbours, ie. the role of the person.

4. If an occupant is informed of the fire by someone else there is a tendency to check this information for himself or herself. This is characteristic of a domestic occupancy as opposed to other occupancy types. Checking the information is related to who gives the information, the role of the individual in his or her own home as well as the proximity of the fire. More responsibility is felt for the safety of others who are likely to be present and for the prevention of damage.

5. Once smoke or fire is encountered, females are more likely to warn others and wait for further instructions. Alternatively they will close the door to the room of fire origin and leave the house. Male occupants are most likely to attempt to fight the fire.

6. Females are more likely to seek assistance from neighbours. Male neighbours are more likely to search for people in smoke and attempt a rescue.

Delaying evacuation in residential occupancies may cause unnecessary deaths. A delay can be caused by many factors, the main reason being the time taken for occupants to become aware of the fire. If a smoke alarm is installed this delay may possibly be reduced and evacuation can be performed safely and faster. Other delays in evacuation are caused by many actions such as, people getting dressed, collecting children, informing others and finding pets. Although these actions are important for the occupant, the time taken to do these tasks must be kept to a minimum. Proulx (1995) investigated the mean delay times for an apartment building. The mean delay time from when the alarm was heard until people began evacuation was 2 minutes and 49 seconds.

People often need to be motivated to evacuate, Canter (1990) details some of the factors that motivate people evacuate as:

- Women are more likely to evacuate immediately than men, who initially attempt to fight the fire.
- If occupants are aware that an escape route exists then they are less likely to leave because they feel less threatened by the fire.
- The presence and density of smoke is directly related to the level of perceived threat, more smoke encourages occupants to evacuate faster.
- Occupants are less likely to leave if they have experienced a fire previously.
- If a fire is judged by the occupants to be extremely serious, then those facing the threat are more likely to leave.

Irwin (1997) found from the New Zealand fire incident reporting statistics that different age groups and genders are more at risk from dying in a domestic fire. Males under five years of age and over 55 years of age have a high death rate and a low injury rate. Males in the 20-24 year age group have a high death and injury rate. Similarly females in the under five years of age category and the 75 – 79 age group category have a high death rate and low injury rate. Females in the 20 – 24 year age group have a high rate of injuries in a domestic fire. These figures are similar to that found around the world. A general trend that can be found is that the very young and the very old are at greatest risk for casualties and death from domestic fires. Reasons for this could be because the very young do not yet have the fire knowledge or the mobility to evacuate and the old do not have the mobility or time to evacuate.

A successful evacuation of a domestic residence depends primarily on the person. If a person's behaviour is adaptive they will most probably evacuate safely. If the public are frequently trained on what actions to take in a fire emergency the less domestic fatalities there will be. It is not possible to regulate houses to make them safer in respect to fire safety therefore peoples behaviour needs to be influenced to make their homes and actions taken in a fire safer.

2.3 Sleep Patterns

When humans sleep, it is not a state of unconsciousness. Rather it is a series of dynamic processes and rhythmical cycles, which reflect different phases of neural functioning with varying sensory thresholds called, sleep states (Nober *et al.* 1981). There are three sleeping states, these are:

- Wakefulness (W)
- Rapid-eye-movement (REM) - A highly activated brain in a paralysed body.
- Non-rapid-eye-movement (NREM) - 4 stages – A relatively inactive, yet actively regulated brain in a moveable body.

The different sleep states alternate through a night's sleep. The routine of sleep and waking behaviour is known as a sleep pattern. Human sleep patterns vary with age and gender. The stage of sleep an occupant is experiencing alters their response to the sound of a smoke alarm. To be effective in a fire event while occupants are sleeping a smoke alarm must be of sufficient intensity to wake humans from sleep.

Familiarity with the stimulus will increase the likelihood of arousal. For example, if a smoke alarm is activated often for training purposes, occupants will recognise the sound and will wake when the smoke alarm is activated at night. As well as sleep stage and familiarity, age and mind altering substances taken, such as alcohol and drugs, affect the sleep and arousal of occupants. Grace (1997) has additional information about sleep patterns and factors that effect them.

If smoke enters persons' bedroom it has the ability to put people in a deeper sleep. This is because one of the principal components of smoke is carbon monoxide. Carbon monoxide, in a high enough dose can cause unconsciousness and death. It is often the public's opinion that the smell of smoke will wake them and therefore they have a casual attitude of keeping smoke alarms operable. An experiment undertaken at the Sleep Disorder Centre at the University of Alabama determined that persons' sense of smell is dulled when asleep and they are therefore less likely to smell smoke when asleep. Only two of the ten subjects were aroused from sleep by a smoke odour (NZFS 1998). This research may not be appropriate because the smoke odour used does not have the same properties as smoke. Not only does smoke smell bad, it is also irritating to the nose and throat, it is possible that smoke can irritate people in their sleep and therefore wake them up.

2.4 Smoke Alarms

Smoke alarms sound an alarm within the room or suite in which it is located when it detects smoke in its vicinity. The two most frequently used types of smoke alarms are the ionisation alarm and the photoelectric alarm. Ionisation alarms use a minute piece of radioactive material to create a field of ions that carry an electric current inside the detectors chamber. When enough smoke particles enter the chamber, the electric current is interrupted, which trips a circuit that activates the alarm. A photoelectric alarm uses a small beam of light aimed at a dark corner in the light-chamber of the smoke alarm. When particles of smoke get in front of the light beam, they scatter the light and reflect it onto a light sensitive photocell. The alarm sounds when an electrical current is produced after enough light is reflected onto the photocell (Irwin 1997).

When activated a smoke alarm emits an intermittent high frequency tone that is intended to wake a sleeping person. Overseas requirements (NFPA 74) are that the smoke alarm should produce a sound pressure level of 85 dBA at a 3m distance. At this level the majority of sleeping occupants would be awoken. However if there is a closed door between the alarm and the sleeping person the sound level at the pillow may be reduced to a level which may not awaken a heavy sleeper.

Smoke alarms in residential dwellings are a useful detection device as they commonly discover the fire more rapidly than other detection devices such as heat detectors. They detect airborne particulate matter from the fire before significant heat build-up occurs. This usually then gives the occupant's additional time to evacuate the premises, try to suppress the fire, or to notify the Fire Service (Irwin 1997).

There are three variables that make a complete fire protection system in a building. These can be seen in Figure 2.1 below.

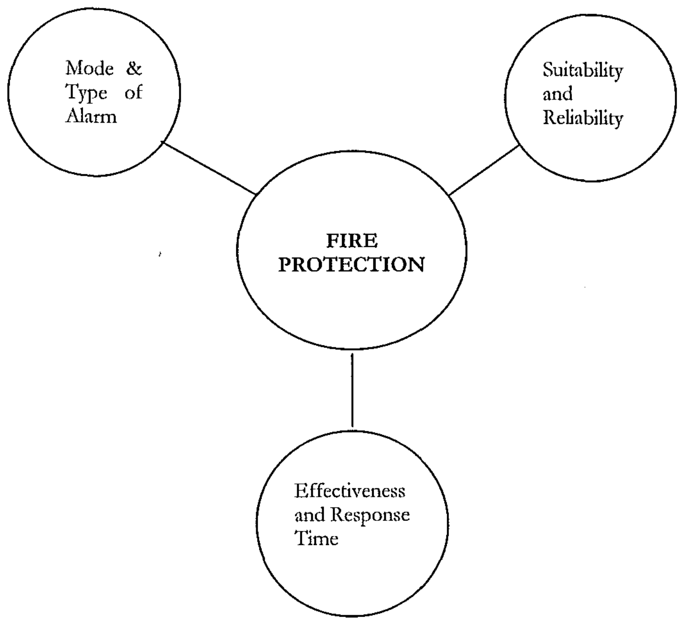


Figure 2.1 Variables of fire protection system in a building

The mode and type of alarm installed vary in their efficiency. The mode and type mean, are there smoke or heat detectors, or sprinklers installed and are these systems automatic or manual.

Any fire protection system must be suitable for the use of the building in which it is installed. They must be maintained and tested so that they are reliable.

Effectiveness and response time varies with the system installed. The type of alarm installed will respond differently than other alarms to the same fire incident eg. if heat or smoke activated. The alarm type installed will also have different effectiveness, for example, sprinklers will suppress the fire but smoke alarms will only alert occupants to a fire incident. The three variables need to work together to achieve a safe and reliable fire alarm system in a building.

Smoke alarms installed in residential houses are both effective and reliable if they are installed and maintained correctly. Smoke alarms are a suitable type of fire protection to put in a residential house because not only are they cheap and simple to install, they also give very early warning of a fire. Although do not suppress the fire, smoke alarms warn occupants quickly enough that they are able to either fight the fire themselves or ring the fire service and evacuate their house. Smoke alarms are also appropriate because they detect flaming fires as well as smouldering fires quickly.

2.4.1 Reliability of Smoke Alarms

Smoke alarms fitted in dwellings can give an early warning of fire, but are only reliable if they are positioned correctly and are regularly tested and maintained. The smoke alarm performance field of the New Zealand Fire Incident Reporting System (FIRS) database has not been recorded particularly well over the years 1986 – 1994. In 1994 a total of 4833 domestic fires occurred throughout New Zealand. There were only 33 reported cases of a domestic smoke alarm in the building operating and 11 cases where the smoke alarm was reported as not operating when a fire incident occurred (Irwin 1997). Studies in the USA show that in the period up to 1995, 93% of homes had at least one smoke alarm installed (Ahrens 1998). The statistics also show that 57% of houses that have had fires had smoke alarms. Of these smoke alarms, 20% of them were non-operational due mainly to their batteries being either dead or missing. Batteries in smoke alarms need to be regularly replaced to keep them operational. Smoke alarms emit a chirping noise when batteries are going flat, this noise is often misinterpreted and either the battery is removed to avoid the noise or it is ignored and the battery is allowed to flatten. Often batteries are removed for use in other electrical equipment.

Smoke alarms cut the risk of dying in a home fire by approximately 50%. However, nearly half of all home fires reported to fire departments still occurred in the now, small share of homes that had no smoke alarms. In a third of the homes that have both smoke alarms and fires, the smoke alarms are not operational (Ahrens 1998).

2.4.2 Who has Smoke Alarms?

Socio-economic factors influence the probability of fire and also the presence of smoke alarms in private dwellings (Decision Research Limited 1996, Ahrens 1998, Munson & Oates 1983, Ogilvy and Mather (Davies 1994)).

Decision Research Limited investigated the penetration rate of smoke alarms into New Zealand households as part of a research project undertaken for the New Zealand Fire Service. They conducted a survey that found that smoke alarms were installed in the homes of 48% of the survey respondents and that in a few areas the household income had an impact on the level of smoke alarm penetration. The result being that the higher the household income, the higher the levels of smoke alarm penetration (Decision Research Limited, 1996). The survey found that operational smoke alarms were installed in 95% of houses. The survey also found that the respondents who owned their own homes were more likely to have one or more installed alarms, than respondents renting or who reported other living arrangements.

A project by the University of Canterbury in Christchurch (Rusbridge 1999) determined that 82% of households have at least one smoke alarm. Of the 141 people surveyed, smoke alarms were more prevalent in middle class households than in lower income households. This project was conducted during a large publicity campaign by the Christchurch City Council who were encouraging the installation of smoke alarms.

A survey conducted by the New Zealand Fire Service in November 1997 set out to determine residential fire risk in lower socio-economic residences in Invercargill, Porirua and Otara. The residences surveyed were typically housing corporation estates that have a high proportion of welfare dependent and unemployed residents from a variety of ethnic and cultural backgrounds. The results of the study show that 55% of residents in Invercargill have smoke alarms, this trails the Southland area average of 70% of homes having smoke alarms. Otara and Porirua have very low proportions of residences with smoke alarms, 28% and 24% respectively.

An overseas study by Munson and Oates (1983) found the following conclusions:

- As income increases the incidence rate of fire decreases.
- Fires are less likely to occur in residences that are owner occupied than in rental dwellings.
- Communities with high social tensions such as high unemployment rates or a larger black population are positively related to higher probabilities of fires.
- Overcrowded dwellings are more prone to fire.

Ogilvy and Mather (Davies 1994) were commissioned by the New Zealand Fire Service to complete a statistical analysis of the community characteristics that are related to incidences of residential fires in New Zealand. Their conclusions show that the community characteristics that effect the incidence of fires in New Zealand are high unemployment rates, high social welfare benefit receipt, low rate of ownership of residence and lower income. Communities with a high population of Maori and Pacific Islanders have a higher risk of a fire incident. Often these high risk groups are less likely to have smoke alarms installed in their houses and therefore the risk of a fatality in a domestic fire is increased.

2.4.3 Typical Location of Smoke Alarms

Typically, smoke alarms are positioned in the hallway outside bedrooms or in the living area. If a household has only one smoke alarm it is recommended to install them where all occupants will hear it when asleep, the logical place is therefore in the hallway outside the bedrooms. If the home is two storey, then smoke alarms should be installed on each level of the stairway as a minimum. If households have more than one alarm it is preferable to have them interconnected so that if one detects smoke and sets off the alarm, they both sound.

There is a New Zealand standard for the installation of smoke alarms (NZS 4514: 1989). The main restriction on smoke alarm placement in the standard is that they should not be located within "dead" air spaces. These are areas in which trapped hot air will prevent smoke from reaching the smoke alarm. The recommended minimum and maximum coverage suggested by NZS 4514:1989 are shown in Figures 2.2 and 2.3.

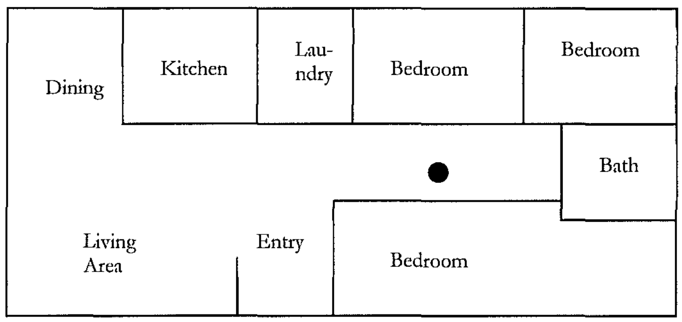


Figure 2.2 Recommended installation of smoke alarms to provide for minimal coverage (from NZS 4514: 1989).

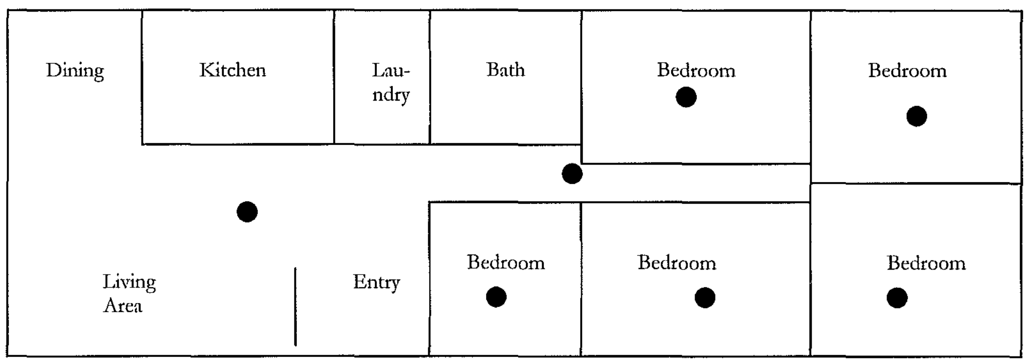


Figure 2.3 Recommended installation of smoke alarms to provide for maximum coverage (from NZS 4514: 1989).

A fire safety cost effectiveness study for residential buildings carried out for the Building Control Commission in Australia (Beever 1999) determined that mains or battery powered smoke alarms in residential houses are cost effective. It was also determined by experimentation that having smoke alarms installed in every room and not just the hallway gives around two minutes extra warning time.

2.4.4 Waking Effectiveness of Smoke Alarms

Smoke alarms need to be loud enough so that all people in a house will wake to it. The sound level of a typical New Zealand smoke alarm is 85 dBA. The acceptable level to wake people is approximately 75 dBA. Doors attenuate approximately 10 - 15 dBA (Smith 1992), therefore if a door is closed a sound level of at least 85 dBA is required.

Various researchers have carried out waking effectiveness studies of people to smoke alarms. The first experiment by Nober *et. al.*(1981) investigated the waking performance of 30 college age subjects to a taped smoke alarm signal calibrated to 55, 70 and 85 dBA at pillow position in their own bedrooms. The 55 dBA level corresponds to measures in the bedroom at pillow position with the door closed and the 70 dBA level is with the door open. The 85 dBA level was the mean value of the alarm within 10ft of the sound source. The response times were measured from alarm activation to switching off the alarm and telephoning the fire department. The results from the experiment showed that time taken to shut off the alarm averaged for the three different sounds to be 13.6 seconds, 9.5 seconds, and 7.4 seconds. The time taken to phone the fire department averaged 70.0 seconds, 61.6 seconds and 53.6 seconds for 55, 70 and 85 dBA respectively. The second experiment was similar but an air-conditioning noise of 53 dBA was used as background noise. Response times were very slow and in some cases subjects did not wake at all. The waking response for the 55 dBA alarm was 43.4 seconds and 18.8 seconds for the 70 dBA alarm. The first experiment gives rapid subject responses. This could be due to the research population being motivated young adult volunteers. Even thought the test environment was in their own bedroom, the expectation for an alarm and the desire to respond well may have influenced the quick response results. The second experiment shows that subjects respond faster when there is a greater signal to noise ratio.

Bruck *et. al.* (1993) investigated how reliably a smoke alarm would awaken a normal sleeper when not trained to expect the signal. An alarm of 60 dBA at the pillow was presented to naive subjects for a maximum of ten minutes uninterrupted, if the person was still asleep the alarm was presented again. All stages of sleep were assessed and alarm activation was carried out at stage four NREM (non-rapid eye movement), stage two NREM and REM (rapid eye movement). Results show that five out of 24 subjects were not aroused by one or more presentations of the alarm. One person did not awaken to the alarm in stage three and four NREM sleep even when the alarm was repeated six times. Some other people slept through the alarm when presented in the REM sleep stage and two cases occurred where a person slept through an alarm in stage two NREM sleep. The data from the experiments showed that the mean latency for awakenings were longer and more variable in stage 4 NREM sleep than in stage 2 NREM or REM sleep.

A study carried out at the University of Canterbury by Duncan (1999) determined the waking effectiveness of a domestic smoke alarm for normal healthy people to be 89%. This was determined by installing a smoke alarm in people's houses and activating them at various times at night and recording the response times. Other findings from the research are that children under the age of ten do not wake up to the smoke alarm before an adult occupant turns it off. The research also suggests that alcohol increases the time to respond to a smoke alarm.

The above researchers all show that response to a smoke alarm is dependent on how loud the alarm is compared to background noise and in what stage of sleep the occupant is in.

2.5 Statistics

The statistics used for the probabilistic risk assessment in this study have, where possible, been sourced from domestic fires that started at night and involved a fatality. They are presented here to provide a background to fire incident frequency within New Zealand.

2.5.1 *New Zealand Fire Service Database*

A few of the statistics used in the probabilistic risk assessment are sourced from the New Zealand Fire Incident Reporting System (FIRS). The FIRS database is based on NFPA 902M Fire Reporting Field Incident Manual (Narayanan and Whiting 1996). The primary objective of FIRS is to provide information:

- to facilitate strategic planning and feedback for operations through
    - the study of trends
    - measurement of the effectiveness of fire safety practices;
- for statistical purposes. (Narayanan and Whiting 1996)

FIRS was first implemented in 1986, it is maintained at the New Zealand Fire Service in Wellington. Every time the Fire Service responds to an alarm, an incident occurs which is then entered into the FIRS database. The incident may be a fire, smoke scare, rescue, false alarm, or hazardous materials situation. In all cases an incident report is to be filled out and later entered onto the FIRS database. The national fire statistics are published annually by the New Zealand Fire Service and are available to the public.

2.5.2 *Where Fires Start*

Domestic Fires – All fires

The most common area of fire origin for all domestic fires over the period 1986 to 1994 was the kitchen (22.2%), followed by the chimney (15.3%), lounges and dining room (14.0%), bedrooms (11.1%), structural areas (8.5%), laundry (3.3%) and other (26.6%), (Irwin 1997).

Domestic Fires – Fatality

It is important to get representative data to use in the risk assessment. As risk to life and probability of failure is being determined for sleeping occupants it is important to get data for fatalities, and if possible fatalities at night time. Bedrooms are the leading area of fire origin for fatal domestic fires (38.2%), lounge and dining room fires are next (25.9%), followed by kitchen fires (24.1%) and other (11.8%), (Irwin 1997). The area of fire origin is used as an event in the event tree analysis. Only the bedroom and living area fire origins are used, as these are most prevalent for domestic fires involving a fatality. Living areas are determined as the lounge, kitchen and other.

2.5.3 When Fires Start

On average between 1986 and 1994, the incidence of residential fires is relatively low during the early hours of the morning. From 6.00am onwards the rate of fires increases sharply until 10.00am where it still increases, but at a lower rate. The rate once again increases sharply after 4.00pm until it peaks between 6.00pm and 7.00pm and then drops away sharply until midnight. The peak at 6.00pm can be attributed to a rise in kitchen fires due to people cooking their evening meals (Irwin 1997). Figure 2.4 displays the average number of residential fires along with those causing injury or a fatality and the time of day that they occur. Fatalities due to fires increase late at night and the early hours of the morning when the majority of people are asleep even though the number of fire incidents is low. A greater number of fire incidents occur in the weekend. The rate of domestic fire occurrence is lowest on Tuesday and it rises steadily through the week until Friday. The rate then peaks sharply on Saturday before dropping back to the same level as Friday on Sunday (Irwin 1997).

The rate of fire fatalities in domestic fire incidents over the 1986 to 1994 period is greatest on Sunday. This fact goes against the obvious trend that, the more fire incidents there are, the more fire casualties or fatalities there will be. This indicates that there is possibly a socio-economic feature at play. The Sunday fatalities involve a greater occurrence of fires started by smoking materials and people falling asleep in the early hours of the morning. The people involved in these fatalities were generally males in their 30's and were in their bedroom at the time and had either been smoking or had gone to bed after forgetting to turn off cooking appliances in the kitchen (Irwin 1997).

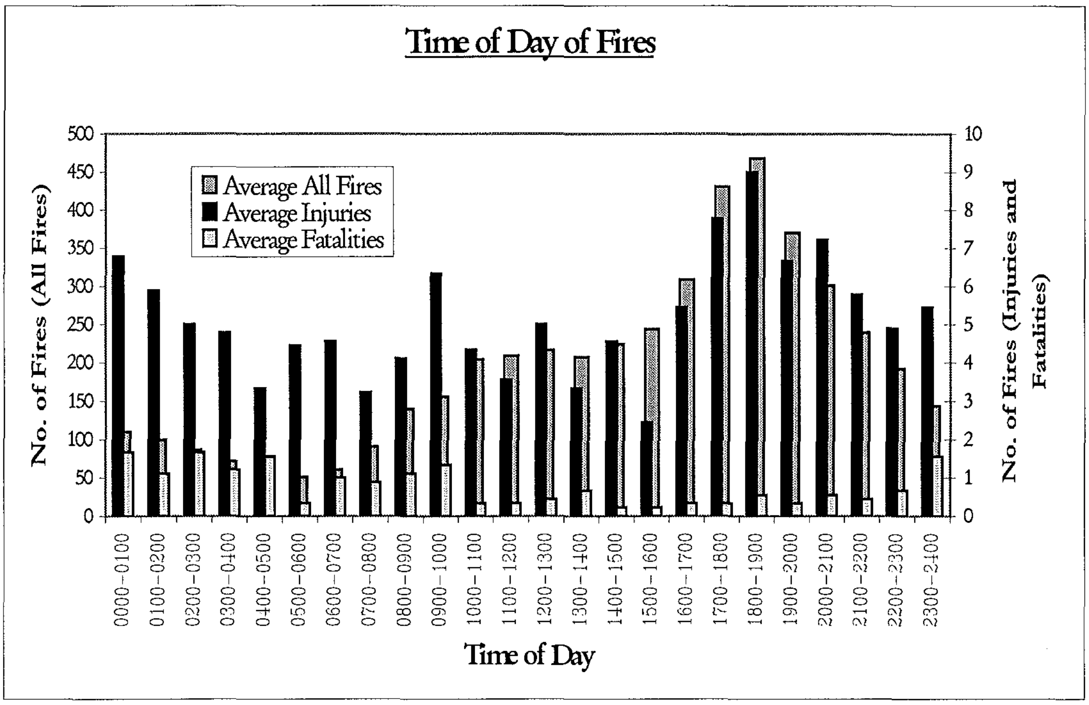


Figure 2.4 Times of day when fires start (data from Irwin 1997)

2.5.4 *Material Fires Start On*

The type of material that is first ignited may be used to determine what sort of fire will develop. It can determine if it is flaming or smouldering or if the fire is slow, medium or fast growing.

Irwin (1997) uses the material composition of the first item ignited that has sufficient volume of heat intensity to extend to self perpetuating or uncontrolled fire as a definition of 'type of material ignited'. New Zealand FIRS data for the period 1986 to 1990 has incomplete records of the first material ignited due to the question often being left blank on the fire incident forms. Of completed fire incident forms sawn wood, including all finished timber products, is the leading type of material ignited with a value of 13.7%. Fabric, textiles and fur is the second most frequent type of material ignited with 11.3%. Plastics were next highest with 8.7%. Plastics include rigid plastics such as PVC and perspex and flexible plastics such as electrical insulation and flexible polyurethane foam. Flexible polyurethane foam had a very low value of 0.3%. This low value may be because many polyurethane foams such as those used in furniture and mattresses are covered with fabric or textiles and therefore that category was entered as the first material ignited. Fat and grease (food) were next highest for the first material ignited with 7.7%. These materials are typically associated with stove top and oven fires.

In 1974 the Fire Journal reviewed 636 residential fires. Investigations into these fires determined that the material that is most likely to be ignited is textile. This was prevalent in approximately 40% of casualty producing fires. In residential fires causing deaths, 49% had 'fabric textile' as the first material ignited. Ignition of furnishing was associated with 19.6% of fatal fires (Loveridge 1998). This data differs from that obtained from the FIRS database.

Chapter 3 Event Tree Methodology

3.1 What are Event Trees?

Event trees are one method of performing a probabilistic risk assessment. Event tree analysis is a technique for evaluating potential incident outcomes resulting from a specific system failure or human error known as an initiating event. The results of event tree analysis are incident sequences, they describe the possible incident outcomes in terms of the sequences of events whether they are successes or failures of safety functions that follow an initiating event.

Each event in an event tree that may or may not happen adds two branches of possibilities to the tree. The end of each branch represents the conclusion to a possible sequence of events in the real world ie. a fire scenario. The probability of the branch is the product of the probabilities of all the events along its length. The probabilities for each of the events at a fork in the tree must add to one. The probability of failure of the event tree is calculated by adding all nodes of failure in one event tree.

An event tree is an excellent risk assessment tool because it is easy to trace the path from a single initiating event until a failure. Doing this shows a clear picture to why a system fails or why a scenario occurs.

The analysis carried out in this study uses eight event trees. Each event tree describes a different scenario as described in Section 3.2. Within each event tree there are a number of events that occur, these are detailed in Section 3.3.

3.2 Event Tree Scenarios

There are eight combinations of event tree scenarios which are derived from the following three parameters each with two options.

- Is there a smoke alarm?
- Is the fire flaming or smouldering?
- Is the door open or closed?

Each event tree is derived from different combinations of these questions. The smoke alarm location is the hallway, this is typical and recommended practice. The bedroom was not used for locating a smoke alarm because it was assumed that if the bedroom had a smoke alarm then it follows that the hallway would too. Therefore, with smoke alarms in both locations, safety is not affected significantly by the position of the bedroom door. The eight scenarios can be seen in Table 3.1.

Table 3.1 Event Tree Scenarios

Scenario Number	Details
1	Smoke Alarm Installed, Flaming Fire, Smoke Alarm in Hall, Door Open
2	Smoke Alarm Installed, Flaming Fire, Smoke Alarm in Hall, Door Closed
3	Smoke Alarm Installed, Smouldering Fire, Smoke Alarm in Hall, Door Open
4	Smoke Alarm Installed, Smouldering Fire, Smoke Alarm in Hall, Door Closed
5	No Smoke Alarm, Flaming Fire, Door Open
6	No Smoke Alarm, Flaming Fire, Door Closed
7	No Smoke Alarm, Smouldering Fire, Door Open
8	No Smoke Alarm, Smouldering Fire, Door Closed

Each scenario forms a pair with another scenario. The only difference between these two scenarios is the position of the door. Each pair of scenarios is known as a set of scenarios.

3.3 Events

The event trees have been constructed from the following questions, or events. The hierarchy of the events on the tree was determined by considering the logical sequence events in a fire, that is, the fire starts, the smoke alarm goes, occupants wake and begin to evacuate.

The following seven questions detail the events used to construct the eight trees.

1. What is the fire location?
2. Does the smoke alarm go?
3. Does the smoke alarm wake the occupants?
4. Are occupants aware of the fire by other means before the smoke alarm goes?
5. Do untenable conditions occur in the egress?
6. Do occupants evacuate themselves?
7. Do occupants evacuate by other means?

To explain what each of these events mean please see the following table, Table 3.2.

Table 3.2 Explanation of Events

Event Question	Explanation
What is the fire location?	Does the fire start in either the bedroom or the living area?
Does the smoke alarm go?	Is there enough smoke at the detector for it to activate. Depends on type of fire, if the door is open or closed and if the smoke alarm is operable?
Does the smoke alarm wake occupants?	If the smoke alarm activates, does it wake occupants? This is dependent on positioning of the smoke alarm and door position.
Are occupants aware of the fire by other means before the smoke alarm activates?	Do occupants become aware of the fire by means other than smoke alarms before the smoke alarm activates? For example, visual, olfactory or by auditory means. If the smoke alarm does not activate or is not present the question

	is do the occupants become aware of the fire by other means?
Do untenable conditions occur in the egress?	Do conditions in the egress become untenable before occupants are aware of the fire, ie. before the smoke alarm activates or before occupants are aware by other means?
Do occupants evacuate themselves?	Do occupants once woken by the fire or by the smoke alarm evacuate themselves through the corridor. Occupants are only able to evacuate themselves if they are aware of the fire.
Do occupants evacuate by other means?	Do occupants evacuate by means other than the main egress (hallway). This could be out a window or could be assisted evacuation by neighbours or the New Zealand Fire Service. This only occurs when occupants are aware of the fire but the egress route in untenable.

3.4 Event Tree Analysis

3.4.1 About Precision Tree

Precision Tree (Palisade Corporation 1997) is a decision analysis add-in for Microsoft Excel (Microsoft 1997). Precision Tree allows the user to easily create decision trees or influence diagrams. Decision trees are the same as event trees. They are a graphical representation of a problem describing chance events and decisions in chronological order. The ease and usefulness of Precision Tree makes it possible to do a comprehensive probabilistic risk assessment of whether bedroom doors should be open or closed. Values and probabilities are entered directly into the Excel spreadsheet cells. The probabilities are multiplied along the branches and the resulting probability is displayed at the end of the branch. The chance node is one of the seven events, or questions, that are along the branch of a tree. These events are outlined in Section 3.3.

3.4.2 Constructing the Event Tree

The event tree was constructed according to the scenarios they are depicting, as described in Section 3.2, and by using the events as described in Section 3.3. Initially the trees appeared as if they were going to be extremely complicated and large with more scenarios and events than described in Sections 3.2 and 3.3. It was decided that detailed trees were not appropriate for the project because of time constraints and problems with obtaining reliable probabilities to input into the tree. The event trees used for analysis can be seen in Appendix I, a sample event tree can be seen in Figure 3.1

It was necessary to find the probabilities of the events occurring from existing data or by using engineering judgement. The probabilities used and the justification for using them can be seen in Section 3.4.3. A failure branch is defined as a branch where occupants do not evacuate to a place of safety. To find the probability of failure for the entire event tree, probabilities were added for all failure branches. The results can be seen in Chapter Five.

It was possible to collapse the event tree in cases where there was only one possible answer to the question. For instance if the smoke alarm doesn't activate then it will not wake the occupants, therefore the second question is irrelevant and the event tree can be collapsed at this point. Collapsing the event tree means it is less complicated and there are fewer calculations to perform.

It was unnecessary to evaluate the expected risk to life for the event trees because the results gained can only be compared relatively with FiRECAM results. To determine whether it is safer to have doors open or closed, each scenario of door open and door closed were compared and the probability of failure noted. A higher probability of failure means that this is the least safe way of leaving the door when sleeping.

The probabilities of events occurring, once initially decided on, were further refined by further discussion with Dr Charley Fleischmann to get more realistic values. It is the refined values that are outlined in Section 3.4.3.

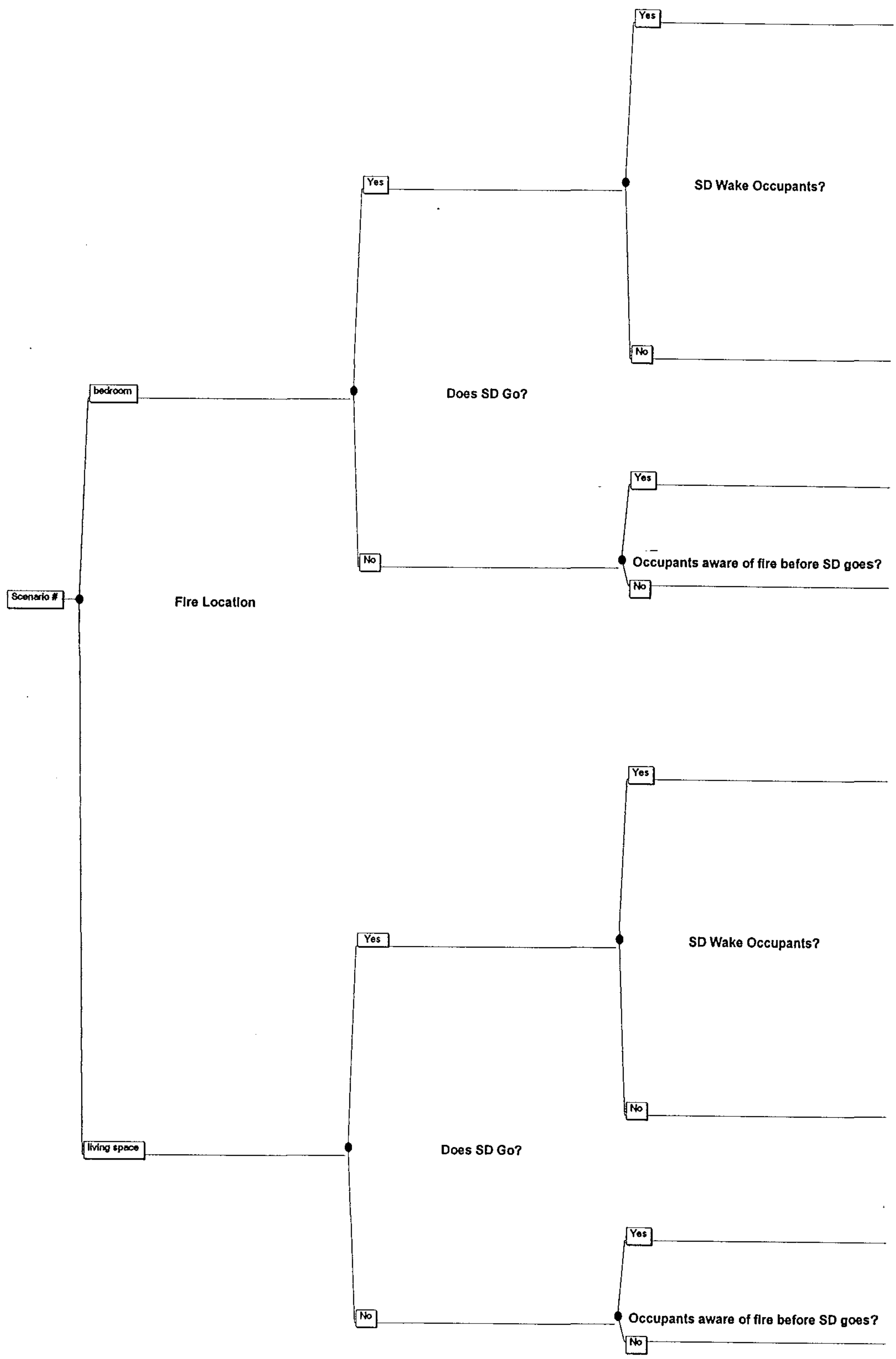
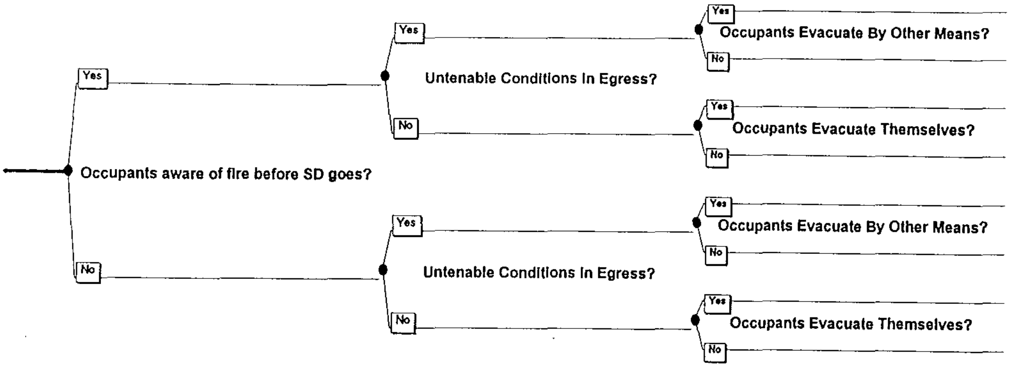
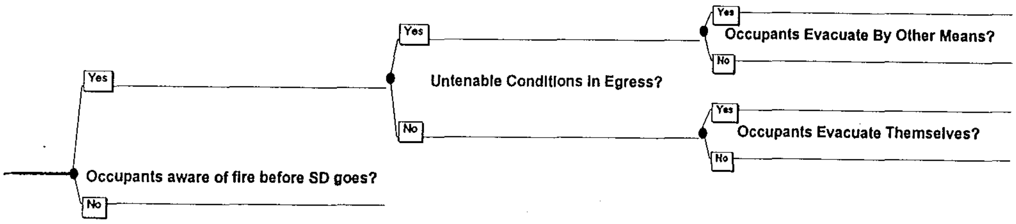
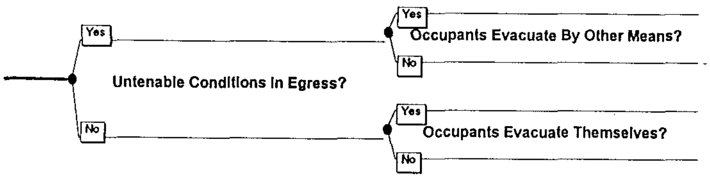
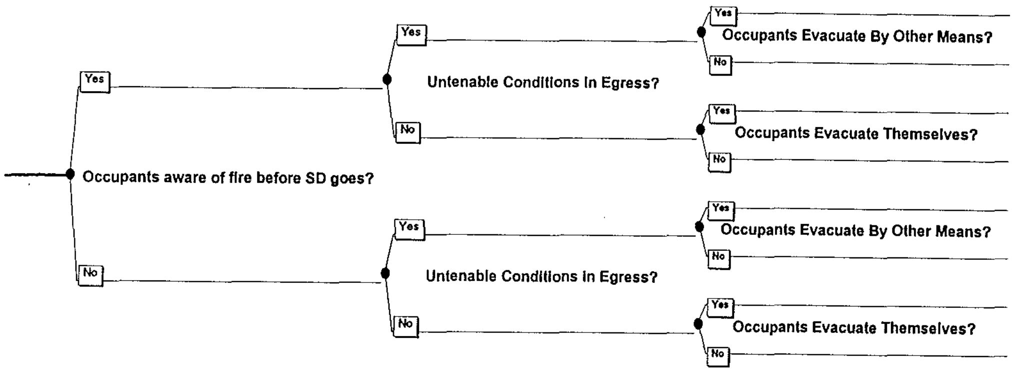


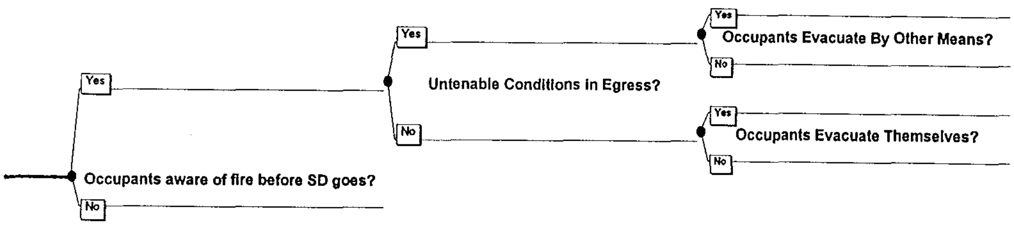
Figure 3.1 Sample Event Tree

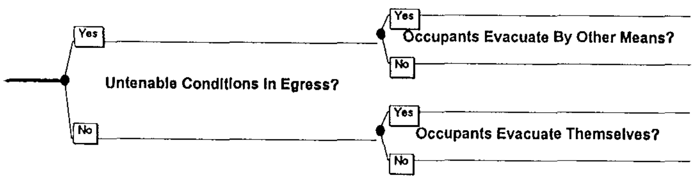

Occupants aware of fire before SD goes?
Yes
No
Untenable Conditions In Egress?
Yes
No
Untenable Conditions In Egress?
Yes
No
Occupants Evacuate By Other Means?
Yes
No
Occupants Evacuate Themselves?
Yes
No
Occupants Evacuate By Other Means?
Yes
No
Occupants Evacuate Themselves?
Yes
No


Occupants aware of fire before SD goes?
Yes
No
Untenable Conditions In Egress?
Yes
No
Occupants Evacuate By Other Means?
Yes
No
Occupants Evacuate Themselves?
Yes
No


Untenable Conditions In Egress?
Yes
No
Occupants Evacuate By Other Means?
Yes
No
Occupants Evacuate Themselves?
Yes
No


Occupants aware of fire before SD goes?
Yes
No
Untenable Conditions In Egress?
Yes
No
Untenable Conditions In Egress?
Yes
No
Occupants Evacuate By Other Means?
Yes
No
Occupants Evacuate Themselves?
Yes
No
Occupants Evacuate By Other Means?
Yes
No
Occupants Evacuate Themselves?
Yes
No


Occupants aware of fire before SD goes?
Yes
No
Untenable Conditions In Egress?
Yes
No
Occupants Evacuate By Other Means?
Yes
No
Occupants Evacuate Themselves?
Yes
No


Untenable Conditions In Egress?
Yes
No
Occupants Evacuate By Other Means?
Yes
No
Occupants Evacuate Themselves?
Yes
No

3.4.3 *Determining Probabilities for the Event Tree*

Probabilities need to be determined for all of the events in the event trees. Some of the events are constant for all trees and some events are scenario dependent. The probabilities are multiplied along the branches and a probability of failure is calculated by adding the probabilities at the end of all of the branches of one event tree. Probabilities were all determined by assuming that the occupants of the house were all healthy and mobile and were not under the influence of alcohol, drugs or any substance that may affect their sleeping.

Probabilities of specific events can be determined in two ways. Firstly by using masses of data that are objectively obtained through statistics collected after fire events. And secondly by using probabilities obtained subjectively using the knowledge and judgement of facts by fire protection professionals. The probabilities used in this event tree research used both methods. Objective probabilities from the New Zealand Fire Service Incident Reporting database (FIRS) were used as factual probability. Where necessary subjective probabilities were obtained from Dr Charley Fleischmann, Dr Andy Buchanan and the author, all from the University of Canterbury Fire Engineering School. It is the subjective probabilities that are determined by engineering judgement, which need further refinement in the event trees.

Location of Fire Origin

The probable locations of fire origin are found in statistics from the New Zealand Fire Service database, FIRS. Section 2.5.2 outlines the various probabilities for where a fire is most likely to originate. The event tree allows two of the most likely fire origin locations, these being either the bedroom or the living area. The living area is defined as the lounge, kitchen and other, these are sections in the FIRS database. The probability of the fire starting in the bedroom is 38% and that of the living area is 62%. The living area was defined as the lounge, kitchen, and other (including hallway and laundry) because it is possible for all of these fires to spread into the main living area. The main living area is the area off the hallway, which is at the other end of the house to the bedrooms. The hallway was not used as a possible location of fire origin because typically there is very little in a hallway that is possible to ignite.

Smoke Alarm Activation

The probability that the smoke alarm activates is determined by finding if the smoke alarm is operable and if modelling showed that the smoke alarm would activate. The operability of smoke alarms was determined from USA statistics where studies found that missing batteries, incorrectly installed or poorly maintained smoke alarms gave the overall operability as 80%. New Zealand statistics from the FIRS database show that smoke alarms, when installed, operated 85% of the time. The lower value of 80% was used as the number of fires used to get the New Zealand statistic was not large.

If there is a smouldering fire and the bedroom door is closed between the fire and the smoke alarm it is assumed that the alarm will activate only 20% of the time. This piece of engineering judgement was used as heat release rate data for smouldering fires was not available and therefore modelling on FAST (Peacock 1997) was not performed and the smoke alarm activation time could not be determined. It is assumed that this judgement would be similar to the result gained if modelling could be used. FAST is a fire zone model that uses engineering calculations to provide fire phenomena in compartmented structures. It can be used to determine temperatures, species concentrations, layer height, optical density, pressures, heat flux, vent flows, flowrate and other data from compartment fires.

Smoke Alarm Effectiveness

Preliminary results from a waking effectiveness study being carried out University of Canterbury shows that most people (89%) will wake up from smoke alarms whether their bedroom door is closed or not (Duncan *pers.comm.*). Other similar effectiveness studies (Nober *et. al.* 1981 and Bruck *et. al.* 1993) give the effectiveness of smoke alarms to arouse normal healthy adults from sleep a high probability. From these smoke alarm effectiveness studies, the probability of being woken by the smoke alarm if it activates was determined to be 90% whether the bedroom door was open or closed.

Occupants Aware of Fire by Other Means before smoke alarm activates

Being aware by other means may be by olfactory, visual, auditory or other means. Occupants can only be made aware by other means if the smoke alarm does not activate, if it has not gone quickly enough or if it has not woken the occupants yet. Being aware by other means before the smoke alarm activates is dependent on two factors, these being where the fire is located and what position the door is in. The following table, Table 3.3, gives the probabilities used in the event trees.

Table 3.3 Probabilities of being aware by other means before the smoke alarm (SA) activates.

Situation	Probability if SA goes	Probability if SA doesn't go
Fire in bedroom and the bedroom door open	50%	90%
Fire in living and the bedroom door either open or closed.	25%	80%
Fire in bedroom and bedroom door closed	95%	90%

The probabilities in this table are higher when the smoke alarm hasn't activated because the question is asking "are occupants aware by other means"? This is different to when the smoke alarm activates because the event is then asking, " are occupants aware by other means before the smoke alarm activates"?

When the fire is in the living area it has been assumed that there are equal probabilities of occupants becoming aware of the fire whether the bedroom door is open or closed. The trend can be justified by looking at real fires that have occurred. One such fire is the Empire Hotel fire in New Zealand where there was not central fire alarm system installed. All occupants in the hotel were aware of the fire, even though some didn't evacuate the building. Due to the hotel occupancy, all of the bedroom doors were closed but still all occupants were aware of the fire. If occupants do not become aware of the fire by other means and the smoke alarm has not woken them then they will die in the fire.

These probabilities have been determined by considering two factors, the occupants location to the fire, and the position of the door.

Untenable Conditions in Egress

The probability of untenable conditions is determined by finding the time to untenability along the occupants egress route and the time that the smoke alarm activates. The egress is either the hallway for living area fires or the bedroom for bedroom fires. From the two times it is possible to find the time available for occupants to evacuate as the time between when the smoke alarm activates and the time when conditions in the egress become untenable. This section firstly describes the time to untenable conditions, then the time to smoke alarm activation for smouldering and flaming fires and finally the probability of untenability is determined. Appendix III gives details of the calculations and computer modelling required to determine the probability of untenable conditions. Section 5.1.1 shows the results of the times for the untenability and smoke alarm activation.

Time to Untenable Conditions

- *Smouldering Fires*

  The time to untenable conditions for smouldering fires could not be modelled on the computer using FAST (Peacock 1997) because accurate heat release data was not available. Instead information from Quintere *et. al.* (1982) was used as the basis for determining this parameter. Smouldering fires cause hazardous conditions due to carbon monoxide in approximately 50 – 150 minutes based on a 4.5% minimum dose criterion. The transition to flaming is also very likely in this period. Hence the hazard of smouldering initiated combustion is either the incapacitation of a person due to the inhalation of carbon monoxide or the transition to flaming combustion which would increase both the carbon monoxide and temperature levels of the combustion products. Both hazards appear to have a similar chance to occur in a period 50 – 150 minutes.

- *Flaming Fires*

  In the US and UK toxic smoke products are recognised as being the major cause of incapacitation and death in fires (Purser 1995). FAST (Peacock 1997) was used to find concentrations of species of carbon monoxide, carbon dioxide and oxygen in the egress route. FAST is a fire zone model that uses engineering calculations to provide fire phenomena in compartmented structures. It determines temperatures, species concentrations, layer height, optical density, pressures, heat flux, vent flows, flowrate and other data from compartment fires. The data can be used for further calculations such as that being used here. Calculations are made using the Fractional Incapacitating Dose method (FID) (Purser 1995) to determine the time when untenable conditions occurred in the egress by using the concentration of species data from FAST. The fractional incapacitating dose is the dose of a toxic product acquired during a short period of time, expressed as a fraction of the dose required to cause incapacitation at he average exposure concentration during that time interval (Purser 1995). The fractional incapacitating doses acquired during each short time period are summed throughout the exposure, incapacitation occurring when the fraction reaches unity. Carbon monoxide is considered the most important toxic product, its most important interaction is an increased rate of carbon monoxide uptake due to hyperventilation caused by carbon dioxide. Carbon monoxide combines with haemoglobin in the blood to form carboxyhaemoglobin (COHb) which results in a toxic narcosis because it reduces the amount of oxygen supplied to the tissues of the body, particularly brain tissue (Purser 1995). Therefore the fractional incapacitating dose was determined using the interaction of carbon monoxide and carbon dioxide. The fractional incapacitating dose is found by relating the dose inhaled by the dose required causing incapacitation. Instantaneous death occurs when the FID reaches unity. For the purposes of this research a lower value is used for safety and to be conservative (Frantzich 1997). The differences in time between using unity and 0.25 is approximately 40 seconds in all of the scenarios which, when looking at the way the probabilities are determined, the values used in the event trees remain unchanged. For example, to determine the time when carbon monoxide becomes incapacitating, the ratio of the COHb concentration at time, t, to the COHb concentration known to cause incapacitation or death is determined. When this ratio reaches 0.25 untenable conditions occur at this time, the ratio is also performed for CO_2. The analysis performed in this research considered the effects of CO, CO_2, and O_2 (for low-oxygen hypoxia) for use in the untenability calculations. For results please see Chapter Five and for further information please see Appendix III.

Time to Smoke Alarm Activation

The time for smoke alarm activation was determined using three methods.

1. For smouldering fires a method described by Mulholland in the SFPE Fire Protection Engineering Handbook (1995) is used.
2. For flaming fires with a closed door between the fire and smoke alarm FAST is used to find species concentrations. This is then used in the Mulholland method as above.
3. For flaming fires with doors open the sprinkler/detector response menu of FPETOOL is used to give smoke alarm activation times.

It is necessary to find the time of smoke alarm activation for one main reason. To determine if conditions become untenable before occupants are able to evacuate their residence.

- *Smouldering Fires*

  Although hazardous conditions may not occur quickly for smouldering fires, it is still important to determine the time in which occupants are advised of the fire by the smoke alarm. Mulholland (1995) determines the time for the smoke alarm to activate by using the electrical output of the smoke alarm, represented by the size distribution of the smoke, and the response function of the alarm. The alarm point of the smoke alarm is defined as a voltage when the alarm will activate from a certain amount and type of smoke. The properties of the smoke are required, as are the volume of the room and the burning rate of the fuel.

  The smoke properties are determined from the tables of Mulholland for smouldering fires or can be determined from the FAST modelling for flaming fires. The burning rate (m) for a smouldering fire was determined by experimental results and from literature reviews by Quintere *et.al.* (1982) to be:

$m = ct$ [g/min] where $c = 0.206$ g/min^2 equation 3.1

The volume of the room is used to determine the smoke concentration in the space. The volume of the room depends on fire location and if the door was open or closed. If the bedroom door was open the entire volume of the bedroom and hallway was used. If the bedroom door was closed then only the volume of the bedroom or the hallway was used depending on the fire origin.

Using the Mulholland method the following limitations were found:

- The method does not take into account filling of the room with smoke before spilling to another room ie. it uses one large volume instead of two smaller volumes.
- Information is lacking on the size distribution of smoke and on the smoke alarm response functions.
- The time for smoke to reach the alarm and the time lag for the smoke to enter the sensing zone of the detector need to be included in the method.

- *Flaming Fires*

As mentioned earlier, there are two ways of finding smoke alarm activation times. The simple way using the sprinkler/detector response model in FPETOOL is used when there is one large space to be modelled, eg. a hallway or a bedroom. The sprinkler/detector response part of FPETOOL calculates the thermal response of a smoke alarm located near the ceiling of a large space. The program assumes an unconfined ceiling therefore the results obtained are conservative. The program requires the height of the room and the location of the alarm in relation to the fire. It also requires the initial temperature of the room, the temperature the alarm activates at, the response time index of the alarm (0 for smoke alarms) and the heat release rate of the fire. If there is a doorway between where the fire is and where the smoke alarm is then FAST must be used to get species concentration of carbon monoxide in the compartment of interest use these values in the Mulholland method as detailed for smouldering fires.

Probability of Untenable Conditions

The probability of untenable conditions occurring in the egress was determined by finding the time available for the occupant to escape. The time to escape is taken as the time between the smoke alarm activating and the time until untenable conditions occur.

A probability of 10% was assumed for conditions to become untenable if occupants had greater than one minute to escape. If occupants had between zero and one minute to escape the probability that untenable conditions occurred was taken as 50%. If occupants had no time to escape it was assumed that untenable conditions occurred 80% of the time. 100% was not used if untenable conditions occurred before the smoke alarm activated because it is not possible to say that the modelling is completely accurate therefore it is not wise to increase the probability to 100%. The different probabilities used can be seen in Figure 3.2, Probability of Untenability.

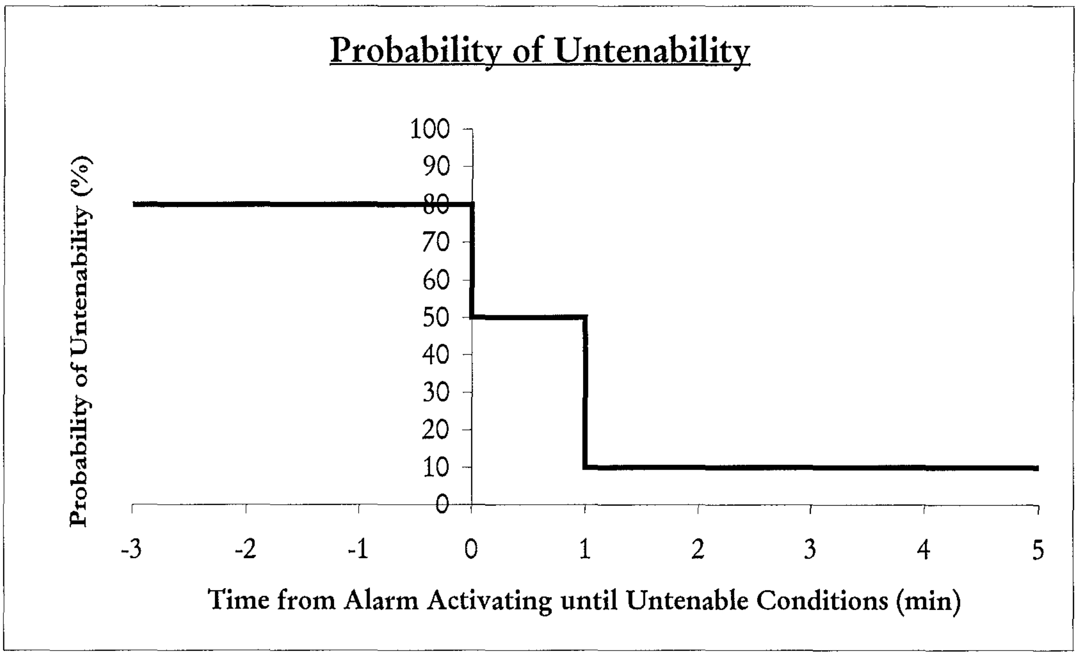


Figure 3.2 Probability of Untenability

If occupants were aware of the fire by other means, before the smoke alarm activated, then it was assumed that the probabilities of untenability were lower than if the smoke alarm had activated. The probabilities of untenability were only lower when the scenarios gave a time from alarm activating to untenable conditions of less than one minute, ie. a probability of untenability of greater than 10%. If an occupant is aware of the fire before the smoke alarm goes, and the smoke alarm goes after conditions become untenable, then it was assumed that the probability of untenability was 10%. This occurs only in one scenario, number two, where the fire is in the bedroom, the bedroom door is closed and the smoke alarm in the hallway takes a long time to activate. It is likely the occupants are aware of the fire a long time before the smoke alarm in the hallway activates and therefore conditions in the egress are not untenable.

The scenarios that have no smoke alarm it is assumed that the untenable conditions occur 10% of the time because occupants will at some time become aware of the fire by other means. If occupants are not aware of the fire by other means then they die.

Exact times to untenability are unknown for smouldering fires because modelling on FAST could not be used. Quintere *et. al.* (1982) determined that hazardous conditions due to carbon monoxide do not occur for approximately 50 – 150 minutes. If the time for smoke alarm activation is less than 50 minutes it is assumed that untenable conditions do not occur in the egress.

Occupants Evacuate Themselves

If an occupant is aware of a fire in their house, then their instinct would be for survival and therefore evacuation. It was assumed that if the occupants were aware of the fire and conditions were tenable then they would evacuate themselves with a 95% probability. If occupants are unaware of the fire then it is assumed that they will die. If occupants are aware of the fire but conditions in the egress are untenable then they must evacuate by other means. The high probability of 95% was used because the event trees are depicting healthy mobile people.

Occupants Evacuate by Other Means

If occupants are aware of the fire but conditions are untenable in their egress route and the fire is either in the bedroom or living area then they have only a 50% chance of evacuating themselves by other means, for example, out the window. This probability is used if the bedroom door is either open or closed for a bedroom fire or if it is open for a living area fire. If occupants are unaware of the fire then they will die. The probability of 50% was chosen because there are many factors against a person successfully evacuating from their house a way other than the main egress route. Some of these factors are:

- the room could be filled with thick black smoke
- occupants may be unfamiliar with a different escape route
- smoke or fire may block other routes such as through a different room
- the window may be too small or difficult to open far enough (the New Zealand Building Code, acceptable solution G4/AS1, Ventilation, states that the window in a bedroom must be 5% of the floor area).

If occupants are aware of the fire but conditions are untenable in their egress route and their bedroom door is closed and the fire is in the living area then they have a 75% chance of evacuating by other means. The higher probability is used here because the room will not be filled with thick black smoke because the door is closed, unlike the other cases mentioned above, and occupants will have more time to think and act in the correct way.

3.4.4 Sensitivity Analysis

A sensitivity analysis of the event trees is required to determine which events the probability of failure is most sensitive to. It is important to know the variables that a final result is most sensitive to, thus showing the need for further research or information in that area. The sensitivity analyses performed on the event trees were carried out using a sensitivity function in Precision Tree. The sensitivity analysis in Precision Tree measures the impact of changing a variable to its extreme values while keeping all other variables constant. The extreme values are determined by varying them by a percentage from the base case. The base case result is the probability of failure from the events as determined above in Section 3.4.3.

Precision Tree performs a one way sensitivity analysis by studying the effect of a single variable or event on the expected outcome of the tree, ie. the probability of failure. To begin the sensitivity analysis the events to be investigated must be determined and maximum and minimum values that the event will be varied by.

Scenarios one and two were used for two different sensitivity analyses. The set of scenarios is used because the trees differ in only one aspect, whether the bedroom door is open or closed. The sensitivities are slightly different for the two event trees because some of the event probabilities differ depending on the position of the bedroom door.

All events for both event trees were used in the sensitivity analysis. All the events apart from 'do untenable conditions occur' and in one case 'are occupants aware before the smoke alarm', were given minimum and maximum values of 10% below and above the base case values. The other events mentioned were given minimum and maximum values 4% below and above the base case because 10% values meant the probability of occurrence would be greater than 100%. The number of steps are entered into Precision Tree to define how many calculations are made between the minimum and maximum values.

During the sensitivity calculation process, the base case value of an event is replaced with the minimum value and the new probability of failure is determined. A set of values ranging from the minimum value for the event up to its maximum are substituted and the probability of failure is calculated for each step. The event is then returned to its base case value and a new event is calculated for its sensitivity.

The results of the one way sensitivity are plotted on a tornado graph, these can be seen in Section 5.1.3, Event Tree Results.

Chapter 4 FiRECAM Methodology

4.1 About FiRECAM[3]

FiRECAM (Fire Risk Evaluation and Cost Assessment Model) is used to assess the expected risk to life and fire costs of specific fire safety designs for apartment and office buildings. FiRECAM can be used to compare performance based designs with code complying designs to evaluate the safest and most cost effective design. FiRECAM uses six design fires in the compartment of fire origin, and the subsequent fire and smoke spread, to evaluate life risks and protection costs for apartment and office buildings. The design fires are shown in Table 4.1.

Table 4.1 FiRECAM Model Scenarios

Scenario	Fire Type	Fire Compartment Door
1	Flashover	Open
2	Flashover	Closed
3	Flaming (non–flashover)	Open
4	Flaming (non-flashover)	Closed
5	Smouldering	Open
6	Smouldering	Closed

The risk-cost assessment model employs an event-based modelling approach in which events are characterised by discrete times and probabilities of occurrence. The event-based approach is used to define the outcomes of fire growth and spread scenarios in terms of the times to occurrence of untenable conditions. The consequence of these outcomes is in terms of the number of people exposed to untenable conditions (Beck and Yung 1994).

[3] All information unless otherwise referenced is from the FiRECAM user manual (Dutcher 1998).

FiRECAM evaluates the cumulative effect of all probable fire scenarios that could occur in the building during the life of the building. It consists of a number of sub-models that simulate the dynamic interaction of fire growth, smoke spread, occupant response and fire department intervention.

For each fire scenario, FiRECAM calculates the expected number of deaths and fire losses. These values are then combined with the probabilities of occurrence of the fire scenarios to obtain the following two decision-making parameters:

1. Expected Risk to Life (ERL) defined as the expected number of deaths over the design life of a building, divided by the product of population of the building and the design life of the building (Equation 4.1).

$$ERL = \frac{Deaths_{BuildingLife}}{Population \times BuildingLife} \qquad \text{Equation 4.1}$$

2. Fire Cost Expectation (FCE) defined as the expected total fire cost which is the sum of capital costs of the passive and active fire protection systems, maintenance cost of the active fire protection systems and expected losses as a result of all probable fire spread in the building. This figure is divided by the cost of the building and its contents (Equation 4.2).

$$FCE = \frac{\sum (Costs_{Protection} + Costs_{Maintenance} + Losses_{Fire})}{\sum (Costs_{Building} + Costs_{Contents})} \qquad \text{Equation 4.2}$$

Only expected risk to life (Equation 4.1) is used in this research, not the fire cost expectation (Equation 4.2), because this research is primarily concerned with life safety. It is possible to turn off the economic models in FiRECAM and only use the models concerned with expected risk to life.

The results derived by FiRECAM are, at the moment, only to be used for comparison and not for an absolute value of risk. The program is conservative and is not yet developed for absolute values of risk.

FiRECAM consists of 15 interconnected sub-models, they are presented below. Each of these sub-models calculates a different set of simulations for fire growth, occupant behaviour, fire department response and fire hazards.

- Building Evaluation Model
- Fire Department Response Model
- Economic Model
- Boundary Element Failure Model
- Design Fire Model
- Fire Growth Model
- Fire Department Action Model
- Occupant Response Model
- Smoke Movement Model
- Evacuation Model
- Fire Spread Model
- Expected Number of Deaths Model
- Expected Risk To Life Model
- Property Loss Model
- Fire Cost Expectation Model

The expected risk to life is calculated from the interaction of the sub-models as shown in the flowchart in Figure 4.1

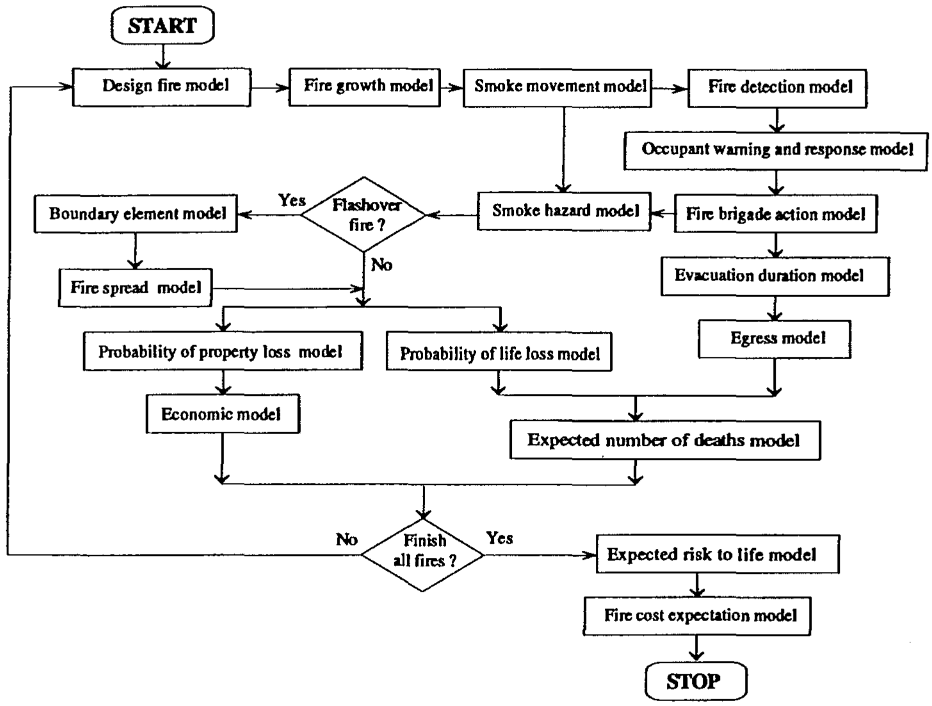


Figure 4.1 FiRECAM Flowchart (Beck and Yung 1994)

To understand how FiRECAM calculates the expected risk to life and the fire cost expectation it is necessary to understand how each of the submodels works. Table 4.2 describes these sub-models.

Table 4.2 FiRECAM Model Description (Dutcher 1998)

Model Name	Purpose
Building Evaluation Model	Computes correction factors for ignition potential, risk and other fire characteristics.
Fire Department Response Model	Computes the response, set-up, and intervention times of a fire department, as well as the probabilities of intervention.
Economic Model	Computes building structural and contents costs, as well as costs for passive and active fire protection and suppression systems.
Boundary Element Failure Model	Computes probabilities of failure of a wall or floor element.
Design Fire Model	Calculates the rate of fire occurrence and the probability of occurrence of a fire scenario.
Fire Growth Model	Models the growth of a fire in a compartment and calculates temperature and toxic gas concentrations as a function of time.
Fire Department Action Model	Computes the intervention times and probabilities. In addition it calculates extinguishment and rescue effectiveness.
Occupant Response Model	Computes occupant response and evacuation probabilities as well as probabilities of no occupant response.

Smoke Movement Model	Computes the smoke hazard based on the temperature and concentration of toxic gases throughout the building as a function of time. In addition, this model computes the critical time before the stairs cannot be used by the occupants to evacuate.
Evacuation Model	Simulates the evacuation of a building, given a floor of fire origin, building population and evacuation destinations.
Fire Spread Model	Computes the probabilities of fire spread using the boundary failure probabilities from the Boundary Element Failure Model.
Expected Number of Deaths Model	Computes the expected number of deaths in a building given the number of trapped occupants and fire and smoke hazards.
Expected Risk To Life Model	Computes the total expected risk to life of a building, based on the expected deaths from all given fire scenarios.
Property Loss Model	Computes the expected economic losses to a building structure and contents given fire and smoke spread, and sensitivity to water.
Fire Cost Expectation Model	Computes the total fire cost expectation of a building, based on the property losses from all given fire scenarios.

FiRECAM is designed for use with multi-storey apartment or office buildings with compartments on each floor. To evaluate a residential dwelling FiRECAM was restricted to one floor and making each room of the dwelling a compartment with reduced fire resistance.

Occupant response to a fire is dependent on what signal the occupants receive telling them to evacuate. A voice communication system gives a high probability of occupants responding whereas smoke alarms give a lower probability of occupants responding and evacuating (Proulx 1994). Occupant response is also affected by sleeping. This project is interested in whether doors should be left open or closed when people are sleeping therefore only the sleeping expected risk to life is analysed. The occupant response model allows extra time delay if an occupant is sleeping. This is added because when an occupant is sleeping, their delay will be increased by the time taken to wake up and to dress.

FiRECAM allows certain users of the program to access additional input file data under its 'Expert Mode'. In Expert mode statistical data in the following categories can be modified:

- Climate and Location
- Building Occupant Response and Action Statistics
- Fire Spread and Failure Statistics
- Fire Spread Numerical Control

- Fire Department Characteristics
- Cost and Economic Data

Because FiRECAM was developed in Canada, the statistics used in the model are either Canadian or American statistics. To adapt FiRECAM to New Zealand it is possible to input New Zealand statistics, if available, into the expert data facility. This has not been done in this research as it was not possible to get the required data within the time constraints. Instead the expert data has been used to refine scenarios as outlined in Section 4.3.2, FiRECAM Scenarios and Section 4.3.3, Expert Data Input.

4.2 FiRECAM Limitations & Assumptions

FiRECAM is still being developed thus there are still some limitations in the model as described by Beck and Yung (1994). The following excerpt is from an article describing these limitations and assumptions of the risk-cost assessment model.

> "In the risk-cost assessment model, due to the complexity and the lack of sufficient understanding of fire phenomena and human behaviour, certain conservative assumptions and approximations were made in the mathematical modelling. In addition, not all aspects of the risk-cost assessment model have been fully verified by full-scale fire experiments or actual fire experience. Only some of the submodels have been verified by experiments or statistical data. As a result, the predictions made by the model can only be considered as approximate. The model, therefore, should not be used for absolute assessments of life risks and protection costs. For comparative assessments of life risks and protection costs, and for the selection of a cost-effective fire safety system design solution, the model is considered to be reliable." (Beck and Yung 1994)

FiRECAM was designed for risk analysis on multi storey apartment or office buildings. Adapting FiRECAM for use on a single level residential house has resulted in some limitations. User's are unable to specify exactly where the fire is to start other than in a compartment or in the open area. The open area does not exist in this model as it is modelled as an apartment building. Open areas only exist in situations such as an office building where there may be small enclosed offices (compartments) and large open areas with many work spaces (open area). Another small limitation in FiRECAM requires that a staircase be installed, this detail influences evacuation, smoke spread and economic costs. FiRECAM also has pre-set building geometries that the user can choose from, it is not possible to input the exact shape of the building being investigated. Nor is it possible for FiRECAM to recognise separate rooms (compartments) such as bedrooms and living rooms as it was designed for multi-storey buildings with compartments that are recognised as apartments.

Entering data into FiRECAM posed additional problems due to the application to a single level dwelling. The lowest fire resistance rating between compartments it is possible to use is 15 minutes. It wasn't possible to have a zero fire resistance rating or a rating of less than 15 minutes. Another input problem related to the fire alarm system that FiRECAM was able to model. It was possible to install just one smoke alarm in the corridor but it was not possible to install only one smoke alarm in only one room. If a smoke alarm was installed in one room/compartment then it was also installed in all other compartments.

The occupant response in FiRECAM depends on the type of alarm that alerts people to the fire. If the alarm operates it is assumed that all occupants will respond to it, the type of alarm effects the level of response. This is a limitation because, in this project, the smoke alarm is not regarded as being effective in waking occupants all of the time. It would be useful for a probability of effectiveness to be used in the FiRECAM calculation of occupant response. In FiRECAM the position of the door also does not effect occupant response. It only effects the smoke spread in a non-fire origin compartment and the expected risk to life, the fire spread failure probability and the smoke spread in a fire origin compartment.

4.3 FiRECAM Analysis

With the ease of use of FiRECAM it was possible to model many different scenarios. These different scenarios often changed only one variable from the base case model. This may have been changing the position of alarm, type of alarm or any other variable as detailed in Section 4.3.1, Entering Basic Data. The different scenarios were modelled mainly to determine the best position for the door to be while sleeping. Other reasons to model the different scenarios were to determine the sensitivity of the model to different variables, investigate different types of houses, smoke alarm locations and fire origins. The expected risk to life calculated by FiRECAM was added for three of the six FiRECAM model scenarios seen in Table 4.1, depending on if the door was open or closed. The expected risk to life was only added for occupants asleep because it is this information that the research is interested in.

4.3.1 Entering Basic Data

In FiRECAM data is entered in either of two ways. By using the input windows or using its expert data package.

Initially the expert data package was not used, as it was not considered necessary. To change the expert data to New Zealand variables would have involved a lot of time collecting the appropriate data. When many FiRECAM trials had been run it was found that the results were very insensitive to many important variables such as if there was a smoke alarm and where it was installed. The expert data was then altered to attempt to try to get better results. The alterations using the expert data package are shown in Section 4.3.3, Expert Data Input.

The initial FiRECAM modelling used the following input data shown in Table 4.3. This scenario is the base case scenario. The base case scenario models a house of simple geometry constructed with concrete and wood. The smoke alarm, which is a central alarm is located either in the corridor or in all compartments/rooms. There is one frequent exit located at the end of the corridor. Six compartments are modelled, this is to represent bedrooms, bathroom/laundry, kitchen and living area. The fire origin is in the compartment. It is not possible to have the fire origin in the living area, or open area, as this does not exist in an apartment building. It is assumed that the living area is a compartment or room in the building.

Table 4.3 FiRECAM Input Data and the parameters it affects

Input	Data	What Input Affects (in terms of Risk to Life)
Occupancy Group	Apartment	Fire Spread Failure Probabilities, Fire Growth and Spread, Occupant response and evacuation, Expected Deaths, Expected Risk to Life
Building Age	10 years	
Building Life	75 years	Expected Risk to Life
Construction	Concrete construction with wood frame interior walls	Fire Spread Failure Probabilities, Fire Spread
Layout (width, length and height)	Rectangular outline with a corridor running lengthwise	Fire Spread Failure Probabilities, Fire Growth and Spread, Smoke Movement, Occupant response and evacuation, Expected deaths and risk to life
No of Compartments	6	Evacuation
% Open Area	10%	Smoke Spread, Evacuation
Window Area	$25m^2$ for entire floor	Fire Spread Failure Probabilities, Fire Spread
No. of Occupants	5	Occupant Response, Evacuation
Occupant Mix	50% male and female 5% special needs 50% senior: children	Evacuation
Exits	1 frequent exit at front door position	Evacuation
Fire Resistance Rating	15 minutes	Fire Spread Failure Probabilities
Alarm System	Central Alarm with bells/horns in either corridor or all compartments	Occupant Response, Fire Department Action
Building Location and Climate	Indoor Temperature 20°C. Average Outdoor Temperature 17°C	Smoke Spread
Fire Origin	In any of the six compartments	Smoke and Fire Spread, Occupant Response, Evacuation, Expected Risk to Life
Fuel Load	Average, $10kg/m^2$ in compartment, $5kg/m^2$ in open area	Smoke Spread, Flame Spread, Occupant Response, Evacuation, Expected Risk to Life
Fire Rated Windows in Fire Origin Compartment	The NO option causes the computer to crash therefore the YES option was used	Smoke and Flame Spread, Occupant Response, Evacuation, Expected Risk to Life

The initial modelling was performed to see how the window area, fire resistance rating and type of construction affected the expected risk to life. The parameters mentioned, as seen in the results, Section 5.2, did not affect the risk to life therefore they have not been varied in the main analysis.

4.3.2 FiRECAM Scenarios

There were three main parameters that were varied to make up the main FiRECAM scenarios, these are:

- Type of smoke alarm and its placement
- Fire Compartment Door – Open or Closed
- Non-fire Compartment Door – Open or Closed

By varying these parameters, 16 different scenarios were modelled as shown in Table 4.4, FiRECAM Scenarios.

Table 4.4 FiRECAM Scenarios

Scenario No.	Smoke Alarm	Fire Origin	Door Situation
1	Compartment Central Alarm	Compartment	All Closed
2	Hallway	Compartment	All Closed
3	Compartment Local Self Contained Alarm	Compartment	All Closed
4	No Smoke Alarm	Compartment	All Closed
5	Compartment Central Alarm	Compartment	Fire Compartment Door Closed, Non-Fire Compartment Door Open
6	Hallway	Compartment	Fire Compartment Door Closed, Non-Fire Compartment Door Open
7	Compartment Local Self Contained Alarm	Compartment	Fire Compartment Door Closed, Non-Fire Compartment Door Open
8	No Smoke Alarm	Compartment	Fire Compartment Door Closed, Non-Fire Compartment Door Open
9	Compartment	Compartment	All Open

	Central Alarm		
10	Hallway	Compartment	All Open
11	Compartment Local Self Contained Alarm	Compartment	All Open
12	No Smoke Alarm	Compartment	All Open
13	Compartment Central Alarm	Compartment	Fire Compartment Door Open, Non- Fire Compartment Door Closed
14	Hallway	Compartment	Fire Compartment Door Open, Non- Fire Compartment Door Closed
15	Compartment Local Self Contained Alarm	Compartment	Fire Compartment Door Open, Non- Fire Compartment Door Closed
16	No Smoke Alarm	Compartment	Fire Compartment Door Open, Non- Fire Compartment Door Closed

There are four different ways of installing smoke alarms in FiRECAM as indicated in Table 4.4, FiRECAM Scenarios. Either no alarm, a self-contained local smoke alarm or a central alarm in the hallway or compartment are able to be modelled. If the local smoke alarm option is used, it installs a smoke alarm in each individual compartment or room. It is not possible to install only a single smoke alarm in one compartment, or to specify where the alarm is to be. A local smoke alarm is a self-contained alarm that is not connected to any other alarm system, only the occupants in the compartment that the alarm activates in are woken. Occupants in other compartments must be woken by other means such as other people or the fire brigade. A central alarm is where all of the smoke alarms in the compartments are interconnected, when one activates all of the alarms sound therefore notifying all occupants of a fire. It is possible to locate any number of smoke alarms connected to the central alarm in either the corridor or the compartments. Once again, if a smoke alarm is installed in a compartment, all compartments will have smoke alarms installed.

4.3.3 Expert Data Input

The expert data input can be used to vary data that is not possible to change in the normal FiRECAM input. For the purposes of this research, the expert data has been changed when problems with the analysis were encountered. One such problem occurred when FiRECAM was found to be insensitive to whether smoke alarms were present or not. By changing the probabilities of the fire compartment door and non-fire compartment door being open to 100% and then 0%, different expected risk to life values were calculated. This alteration gave expected risk to life values that were more appropriate to the analysis. This methodology proved to give reasonable results and these alterations were used throughout the analysis as indicated by Table 4.4, FiRECAM scenarios.

Chapter 5 Results

5.1 Event Tree Results

5.1.1 Times for Smoke Alarm Activation and Untenable Conditions

The method of determining times for smoke alarm activation and for egress conditions to become untenable were detailed in Section 3.4.3. Table 5.1 gives the results for the times when the smoke alarm activates and when conditions become untenable.

Table 5.1 Times of Smoke Alarm Activation and Untenable Conditions

Scenario No.	Smoke Alarm Activation Bedroom Fire (s)	Smoke Alarm Activation Living Fire (s)	Untenable Conditions Bedroom Fire (s)	Untenable Conditions Living Fire(s)
1	124	130	360	420
2	306	130	260	420
3	960	1140	50-150 minutes[1]	50-150 minutes
4	Not activate[2]	1140	50-150 minutes	50-150 minutes
5	No SA[3]	No SA	360	420
6	No SA	No SA	260	420
7	No SA	No SA	50-150 minutes	50-150 minutes
8	No SA	No SA	50-150 minutes	50-150 minutes

Note 1: 50 – 150 minutes is used as it was not possible to model a smouldering fire, see Section 3.4.3.

Note 2: The smoke alarm did not activate due to a smouldering fire with the bedroom door closed between the fire and the smoke alarm.

Note 3: There is no smoke alarm (SA), therefore it could not activate.

5.1.2 Probability of Failure

Failure in the event tree is defined as the end of a branch where people do not evacuate from the house. This could be due to them not hearing the alarm, because of untenable conditions or because occupants were unable to evacuate themselves. The probability of failure for the event tree is calculated by adding together the probabilities at the end of the failure branches. Each of the eight event trees has a probability of failure as defined below in Table 5.2.

Table 5.2 Probability of Failure for each event tree scenario

Scenario	Probability of Failure	Door State
1	0.172	Open
2	0.150	Closed
3	0.131	Open
4	0.138	Closed
5	0.24	Open
6	0.23	Closed
7	0.24	Open
8	0.23	Closed

Figure 5.1 shows a pictorial representation of the same data. Scenarios one and two, three and four, five and six, and seven and eight are plotted as sets to show the differences in failure probabilities depending on whether the bedroom door is open or closed.

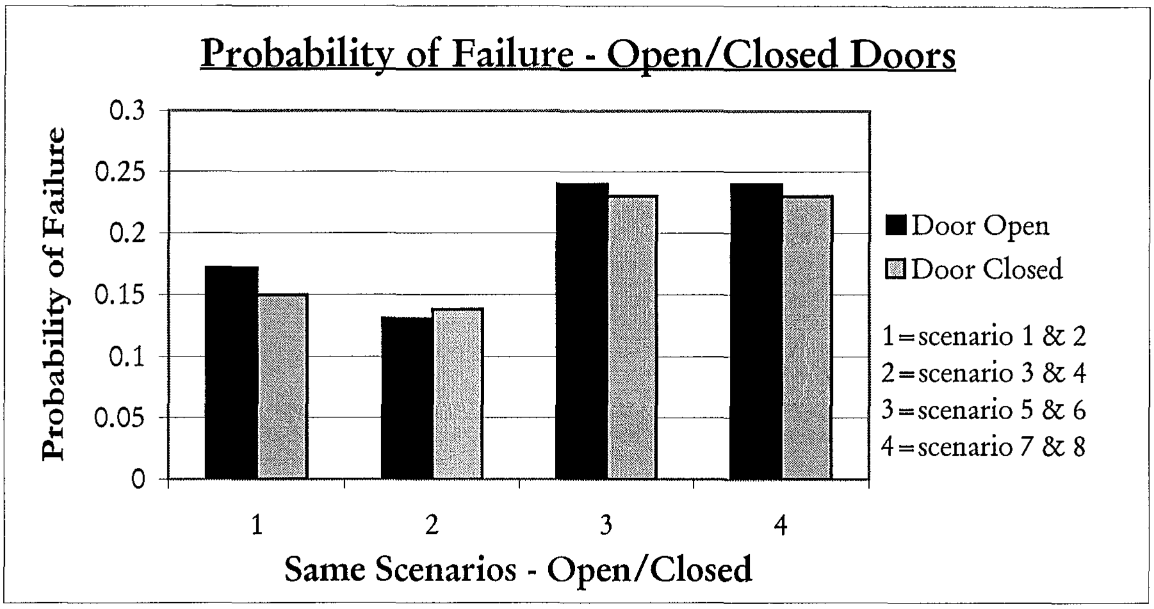


Figure 5.1 Probabilities of failure for the four pairs of scenarios, each differing only in bedroom door position.

The result that is obtained from the probabilities of failure is that it is safer to sleep with the bedroom door closed. In only one of the eight scenarios is it safer to sleep with the bedroom door open. This is scenario four when there is a smouldering fire and the smoke alarm is in the hall. This is not a common scenario therefore when considering the results of the other event trees and the likelihood of them occurring, it is safer to sleep with bedroom doors closed.

5.1.3 Sensitivity Analysis

The sensitivity analysis was performed for all events in the event tree. The tornado graph Precision Tree produces compares the results of the multiple analyses. For each event, a bar is drawn between the extreme values of the probability of failure as calculated from the minimum and maximum values, a vertical line marks the base case probability of failure. The variable with the greatest range between minimum and maximum value is plotted on the top of the graph, it is this event that has the largest impact on the probability of failure. Sensitivity analyses have been performed on scenarios one and two and can be seen in Figure 5.2a and 5.2b.

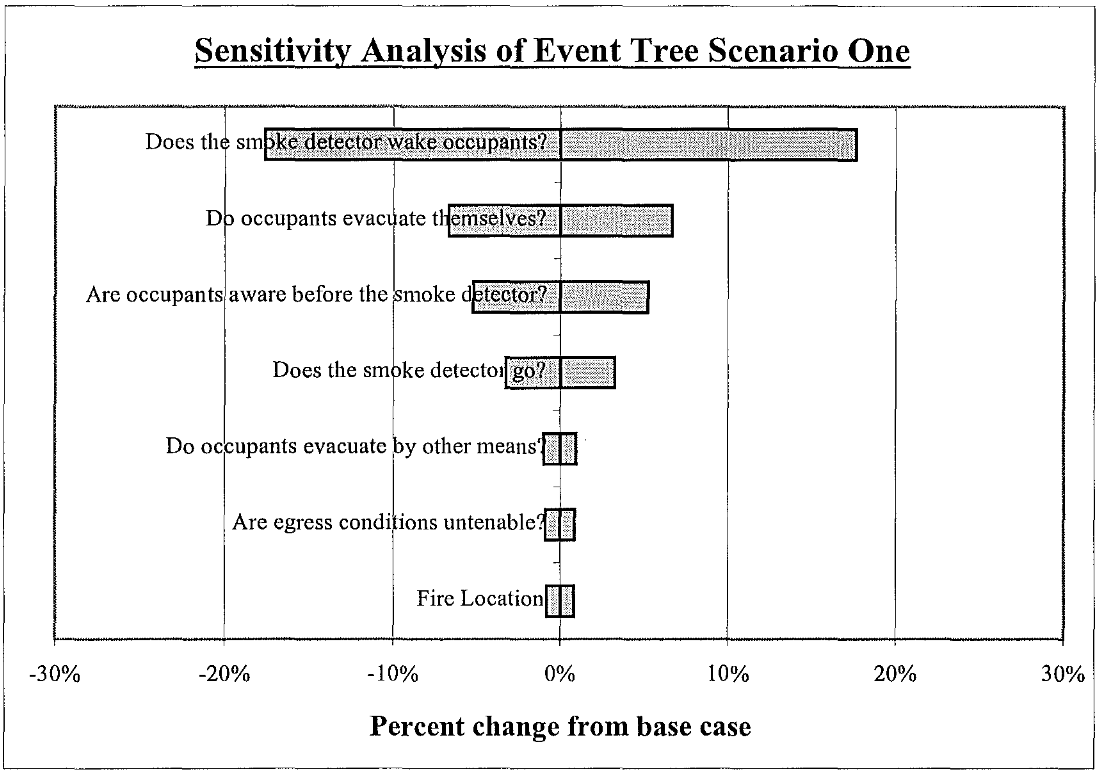


Figure 5.2a Sensitivity of scenario one event tree

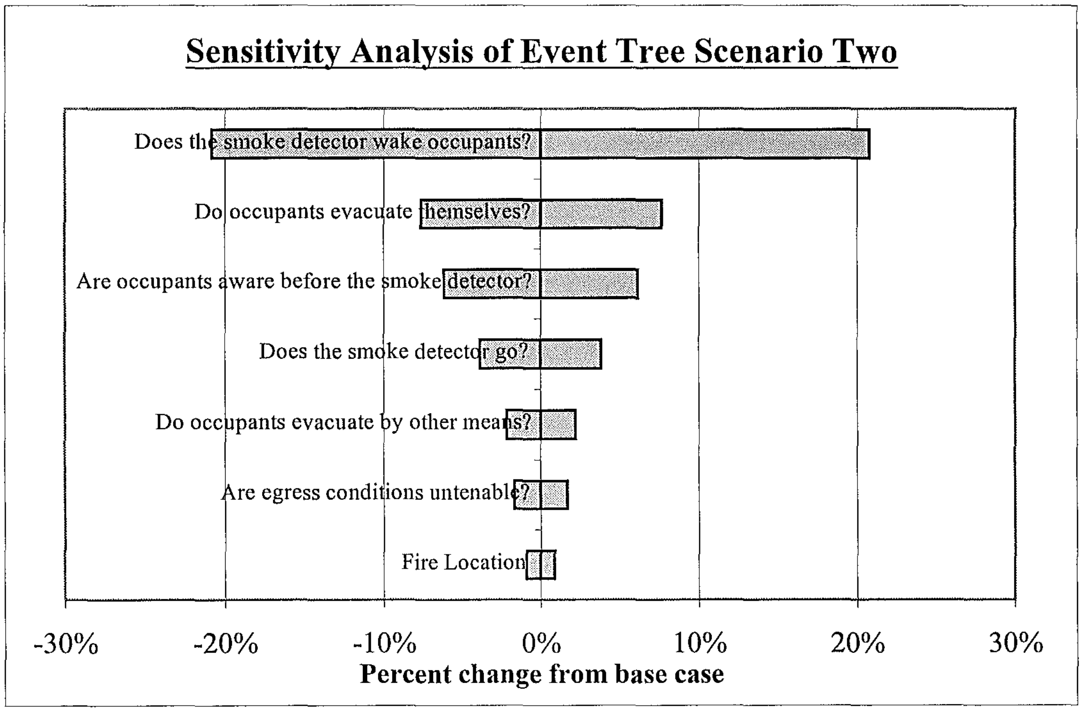


Figure 5.2b Sensitivity of scenario two event tree

As can be seen by these graphs, the sensitivities of the events in the two scenarios have the same sequence but a different magnitude.

5.2 FiRECAM Results

5.2.1 Initial Modelling - Sensitivity

Initial modelling on FiRECAM was performed to show that the window area, type of construction and fire resistance rating did not affect the expected risk to life. The base case scenario was used and altered for these scenarios. Table 5.3 shows the scenarios modelled and their respective values for expected risk to life.

Table 5.3 Initial Modelling of Scenarios

Scenario Description	Expected Risk to Life
Base Case - All doors closed, SD in cmpt, fire in cmpt	8.525E-05
Window area reduced to 1.5m^2	8.525E-05
Window area increased to 40m^2	8.525E-05
All concrete construction	8.525E-05
Fire Resistance Rating increased to 30 minutes	8.525E-05

5.2.2 Expected Risk to Life

The expected risk to life was found from the output data in FiRECAM for the 16 scenarios. Only the expected risk to life when occupants were sleeping were used. A description of the scenarios can be seen in Section 4.3.2, FiRECAM Scenarios. Table 5.4 gives the expected risk to life for the 16 scenarios.

Table 5.4 Expected Risk to Life

Scenario No.	Expected Risk to Life	Door Situation
1	8.525E-05	All Closed
2	8.940E-05	All Closed
3	2.590E-04	All Closed
4	2.643E-04	All Closed
5	8.525E-05	Fire Compartment Door Closed, Non-Fire Compartment Door Open
6	8.940E-05	Fire Compartment Door Closed, Non-Fire Compartment Door Open
7	2.590E-04	Fire Compartment Door Closed, Non-Fire Compartment Door Open
8	2.643E-04	Fire Compartment Door Closed, Non-Fire Compartment Door Open
9	3.976E-04	All Open
10	5.516E-04	All Open
11	7.581E-04	All Open
12	7.624E-04	All Open
13	3.976E-04	Fire Compartment Door Open, Non-Fire Compartment Door Closed
14	5.516E-04	Fire Compartment Door Open, Non-Fire Compartment Door Closed
15	7.581E-04	Fire Compartment Door Open, Non-Fire Compartment Door Closed
16	7.624E-04	Fire Compartment Door Open, Non-Fire Compartment Door Closed

Overall, this table shows that it is safer to sleep with your bedroom door closed because they give the lowest expected risks to life. Other conclusions from this table are that the door of a non-fire compartment makes no difference if it is open or closed to the expected risk to life but the fire compartment door does, and having a smoke detection system interconnected in the compartments is the safest option.

It was possible to find which FiRECAM model scenario gave the largest contribution to the expected risk to life by looking at each scenarios output file. The biggest contribution to the expected risk to life in all cases was a non-flashover flaming fire when the fire compartment door was closed. This gave a percentage contribution of approximately 30%. If the fire compartment door was open the biggest contributor to the expected risk to life is a flashover fire with an average percentage contribution of approximately 45%.

5.3 Comparison of Event Tree and FiRECAM Analysis

The event tree and FiRECAM analysis is modelling the same scenario. This scenario is a single storeyed, simple geometry house with one smoke alarm either placed in the hallway or in the occupants' bedroom. The major differences in modelling between the two method are outlined below.

- The event tree method modelled two fire locations but FiRECAM allowed only one, fire origin in any of the six compartments.
- The geometry of FiRECAM building was as closely modelled as possible to the event tree building, as seen in Figure 1.1a & b.
- Six compartments were modelled in FiRECAM to simulate bedrooms, kitchen, living area and bathroom/laundry.

A relative comparison is possible between the results of FiRECAM and the event tree results. Absolute value comparisons are not viable as the event tree is very simplified and FiRECAM is still under development and is not yet ready for absolute risk comparisons.

The overall result is that both the FiRECAM analysis and the event tree analysis agree. They both show that the safest way to sleep is with the bedroom door closed.

Chapter 6 Discussion

6.1 General

The recommendations to keep bedroom doors open or closed while sleeping given by various people and organisations, as detailed in the literature review, do not always consider all of the possible scenarios. For example, a study and literature review carried out by BRANZ (Collier 1998) considered a scenario of a fire inside a bedroom with the alarm located outside the bedroom. The reasoning behind their recommendation of keeping the door open is that occupants need to be able to hear the alarm when sleeping. Another reason for keeping the bedroom door open was that lethal conditions occur in the bedroom before the alarm, which is outside of the bedroom, will respond if the door is closed. Therefore, keeping the door open will mean the smoke alarm will be able to respond faster and alert occupants to the fire faster. This study did not consider the possibility of occupants becoming aware of the fire in their bedroom by their own means, probably before a smoke alarm activates.

Other recommendations to keep bedroom doors closed while sleeping, such as that given by the New Zealand Fire Service, are often not backed up with any technical evidence. The main reason why the fire service recommends that doors be kept closed is so that smoke and fire does not spread into the occupants' bedroom. The New Zealand Fire Service do mention that all occupants must be able to hear the smoke alarm. This is acceptable as long as occupants are aware of the fire. If the smoke alarm is outside the bedroom door and the occupant is a heavy sleeper, they may not be woken and therefore will be unaware of the fire until it is possibly too late to escape its effects.

As can be seen there are two trains of thought on whether to keep bedroom doors open or closed. On one hand, if bedroom doors are open the awareness of the fire is most probably faster than if the door is closed but the risk of the fire spreading to the bedroom is greater. If the bedroom door is closed then the risk of the fire spreading to the bedroom is low and the chance of being aware of the fire is also lower. It is important that these two factors are balanced, that is, the awareness of the fire must be balanced with the risk of the fire spreading.

The probabilistic risk assessment carried out in this research project was performed to determine if it was safer to sleep with your bedroom door open or closed. The analysis performed using event trees and FiRECAM came up with the same recommendation, to keep the bedroom door closed while sleeping. Both sets of analysis are not considered complete, there are problems with both methods that further research can alleviate.

The research carried out in this project is based on a typical New Zealand house. There is one smoke alarm and occupants are assumed to be healthy, mobile and not under the influence of any sleep altering substances such as alcohol or drugs. It is important to understand that the recommendation given is based on these guidelines. It is always possible to have a house that is not 'typical' or occupants that are not healthy and mobile therefore the recommendation given may not always be the safest for all situations.

6.2 Event Trees

The event tree analysis determined that it is safer to sleep with the bedroom door closed. The analysis has many assumptions and problems associated with it. The problems need to be remedied before more accurate results are determined and before results can be compared closely with the FiRECAM results. The event trees are too simplified and not accurate enough for absolute comparisons of risk to be made. The most likely scenarios for the event tree method are scenarios one and two, where the smoke alarm is located in the hall and there is a flaming fire.

Although the event trees agree with the results from FiRECAM, they are still not complete and entirely correct. A few of the probabilities in the event trees have been found from factual data but most probabilities have been determined by using engineering judgement. The probabilities determined by engineering judgement are the probabilities that are most likely to be incorrect. This is because no actual experiments or data were used to determine the probabilities and there is a lack of basic information.

Instead, knowledge gained from experience and known fire and human behaviour has been used to determine the probabilities.

In order to generate more accurate probabilities for use in the event tree further research needs to be concentrated in two areas. One of these would to be to find actual data on the events. If this is not possible then the probability should be determined by consultation within a Delphi group. A Delphi group is a group of experts. The experts may be from fields such as fire growth and spread, human behaviour, smoke alarm activation and householders, the people involved in domestic fires. Many of the probabilities that need to be determined are scenario dependent, therefore, by using the knowledge of a wide ranging group of people it is more likely that better probabilities will be determined.

The event tree probabilities that were determined from factual data, in some cases, were sourced from statistics for fires at night involving a fatality. In hindsight it would have been better to use statistics from all fires occurring at night. This is because the event tree is not only modelling failures, it is also modelling successful evacuation therefore, all fires should be modelled including those involving fatalities and those not.

The differences in failure probabilities for the scenarios when the bedroom door is open or closed are large in relative terms. The results of the event trees show that it is safer to sleep with the bedroom door closed. In all but one set of scenarios it is safer to sleep with the bedroom door closed. Scenario three and four, a smouldering fire with the smoke alarm in the hallway, gave a higher probability of failure for the bedroom door closed than open. This is to be expected because the probability of the smoke alarm activating is low if the door is closed, as is the probability of untenable conditions occurring if the door is open or closed. Therefore, if the door is open, the occupants can hear the alarm and conditions are not untenable. Scenarios three and four are two of the most unlikely scenarios to occur. Statistics show that non-flashover flaming fires occur most often and smouldering fires least often in sleeping occupancies. This information is sourced from the FiRECAM expert data.

The probabilities of events are often the same for all scenarios, this occurs for the location of the fire origin, operability of the smoke alarm and effectiveness of the smoke alarm. Other probabilities of events such as awareness by other means, untenability in the egress and evacuation by other means are all scenario dependant. It is these events which govern the results of the event tree. For example, if an occupant is required to evacuate by other means and the fire is in the living area, evacuation will be safer if the bedroom door is closed because there is no thick black smoke to impede their decision making and resulting actions. Untenable conditions in the egress are scenario dependent because the probabilities are determined from the activation time of the smoke alarm and the time that the egress becomes untenable. The times are determined from modelling each scenario as described in Section 3.4.3 of this report.

The sensitivity analysis performed by Precision Tree on scenarios one and two found that the two trees are sensitive to the same sequence of events but are sensitive by different magnitudes. The event that caused the largest variation from the base case is 'does the smoke alarm wake occupants?', this is because it is a high value very early on in the sequence of events in the trees. Because of this, any slight change in the probability will effect the calculations greatly. The next event that the probability of failure is most sensitive to is 'do occupants evacuate themselves?', once again this is a large probability but is at the end of the branches on the tree. The next event that the probability of failure is sensitive to is 'are occupants aware before the smoke alarm activates?'. These last two events are scenario dependent, that is, the probabilities depend on what the scenario is depicting. Because of this, more research and work needs to be undertaken to determine more realistic and reliable probabilities.

6.3 FiRECAM

Although the results of FiRECAM show that it is safer to sleep with the bedroom door closed, there are many problems and limitations in the analysis. The most likely scenario for the FiRECAM analysis is when the smoke alarm is positioned in the hallway and the fire is in the bedroom. The fire location is in the bedroom because it is only possible to specify this one location, it is not yet possible to have the corridor as a place of fire origin and there is no open area in the house being modelled. Modelling only the bedroom as a location of fire origin differs from the event tree analysis where fire location is defined as the bedroom or the living area.

The simple scenario modelled was a single storey, rectangular geometry house with six compartments. Each compartment was assumed to be a room, such as a kitchen, living area, bathroom or bedrooms. It was possible to specify the smoke alarm system to be in either the bedroom or the corridor outside the bedrooms. This is typical of the recommendations that smoke alarms should be placed outside bedroom doors or as well as this, in each bedroom. The type of alarm system chosen altered the expected risk to life calculated by FiRECAM. The highest expected risk to life was gained by having no smoke alarms installed, this result is to be expected. If a smoke alarm was installed in a hallway, a slightly higher expected risk to life was given than if smoke alarms were installed in every compartment and were interconnected (a central alarm). If a local smoke alarm was used and installed in every compartment the expected risk to life was only slightly lower than if no smoke alarms were installed. This may be because FiRECAM assumes that a local smoke alarm activating in a compartment will not notify other occupants in other compartments. People in the compartments where the local smoke alarm does not activate, must be notified of the fire by other occupants or the fire brigade. The type of smoke detection system installed influences the occupant response of people in the building. FiRECAM models occupant response depending on the signal that the occupants receive telling them to leave the building. Smoke alarms give a lower probability of occupants responding and evacuating than other systems such as a voice communication system. FiRECAM assumes that occupants receiving a smoke alarm signal from a fire event will look for more information before deciding to evacuate.

It was found that FiRECAM has many limitations when it was used to model a single level house of simple geometry. These limitations have been described in Section 4.2, FiRECAM limitations and assumptions. Good results are not affected by most of the limitations, however, a few of the limitations reduce the usefulness of the model. One of the largest problems was that it is not possible to model a fire in the living area or hallway. It is assumed that the living area is at the other end of the house to the bedrooms. Originally when first using FiRECAM it was thought that the open area could be used as the living area. After consultation with the developers of FiRECAM it was determined that there is no open area in this apartment model, and as mentioned earlier only a fire in the bedrooms can be modelled.

Having a door open or closed does not affect an occupant's response to an alarm outside their door. It is assumed that if an alarm activates then occupants will respond as determined by the occupant response model, the situation of the door does not affect this. The only thing that the door situation of a non-fire compartment effects is the smoke spread into the room. The door situation of the fire compartment effects the expected risk to life, the fire spread failure probability and the smoke spread.

Initial modelling undertaken on FiRECAM gave some interesting results. It was found that the model was not sensitive to the installation and type of smoke alarms. Although the results varied whether the bedroom door was open or closed, the difference in the results between types of smoke alarms or no smoke alarms were insignificant. By altering the expert data this problem was alleviated. It was found that by changing the probabilities of the fire compartment door being open in the expert data the results changed significantly. The probabilities in the expert data were changed to model the compartment doors always being closed, and then always open. Changing the expert data gave different expected risks to life for central smoke alarms in the hallway or compartments, local self-contained smoke alarms in compartments and no smoke alarms. The values obtained are as expected with central smoke alarms (interconnected) in the bedrooms the safest option and no smoke alarms the least safe option.

Sensitivity to other parameters has been investigated by the FiRECAM developers and were found to be reasonable. The following excerpt from an article by Beck and Yung (1994) describes parameter sensitivities.

> "As in many computer models, the model uses certain input parameters to describe the characteristics of various fire safety designs. These include the fire resistance rating of boundary elements, the reliability of smoke alarms and sprinklers, the probability of door open or closed and the response time of fire brigades. Sensitivity of these parameters on the predicted risks have been checked and found to be reasonable."

Initial modelling as described in Section 4.3.1, entering basic data, determined that the expected risk to life is insensitive to window area, construction type and fire resistance rating. This could be because the scenario modelled is only a simple single storey dwelling and these parameters are not significant enough to alter the expected risk to life.

The largest percentage contribution to the expected risk to life was determined from the FiRECAM output. For all scenarios the largest contribution is when the fire compartment door is closed and there is a non-flashover flaming fire. The largest contributor when the fire compartment door is open is a flashover fire. One of the main reasons that the non-flashover fire is a large contributor when the compartment door is closed is because a non-flashover fire has the highest probability of occurring in an apartment fire. Smouldering fires occur the least amount of times and flashover fires occur only slightly more often than smouldering fires. This information is sourced from the expert data files in the FiRECAM program.

Chapter 7 Conclusion & Recommendations

Bedroom doors should be kept closed while people are sleeping. This recommendation has been determined by two methods of probabilistic risk assessment, using event trees and FiRECAM, a fire risk evaluation and cost assessment model developed at the National Research Council of Canada.

Both sets of analyses agree with each other but are not comparable in an absolute sense, they can only be compared relatively. The event tree method and FiRECAM both have assumptions, limitations and problems that further research can address, as discussed in Chapter Six, Discussion.

The recommendation of keeping bedroom doors closed is based on a typical scenario. That is, a single smoke alarm placed outside the bedrooms in a typical residential house. The ideal situation for a domestic house is to have inter-connected smoke alarms installed in all of the bedrooms, in the hallway outside the bedrooms and in the living area. Having smoke alarms throughout the house provides the ultimate protection for occupants, for this case the door situation has very little effect on occupants safety.

The recommendation to keep bedroom doors closed while sleeping is important advice that the New Zealand public must be informed of. Although they may not heed this advice it is important that the New Zealand Fire Service promotes the best practice.

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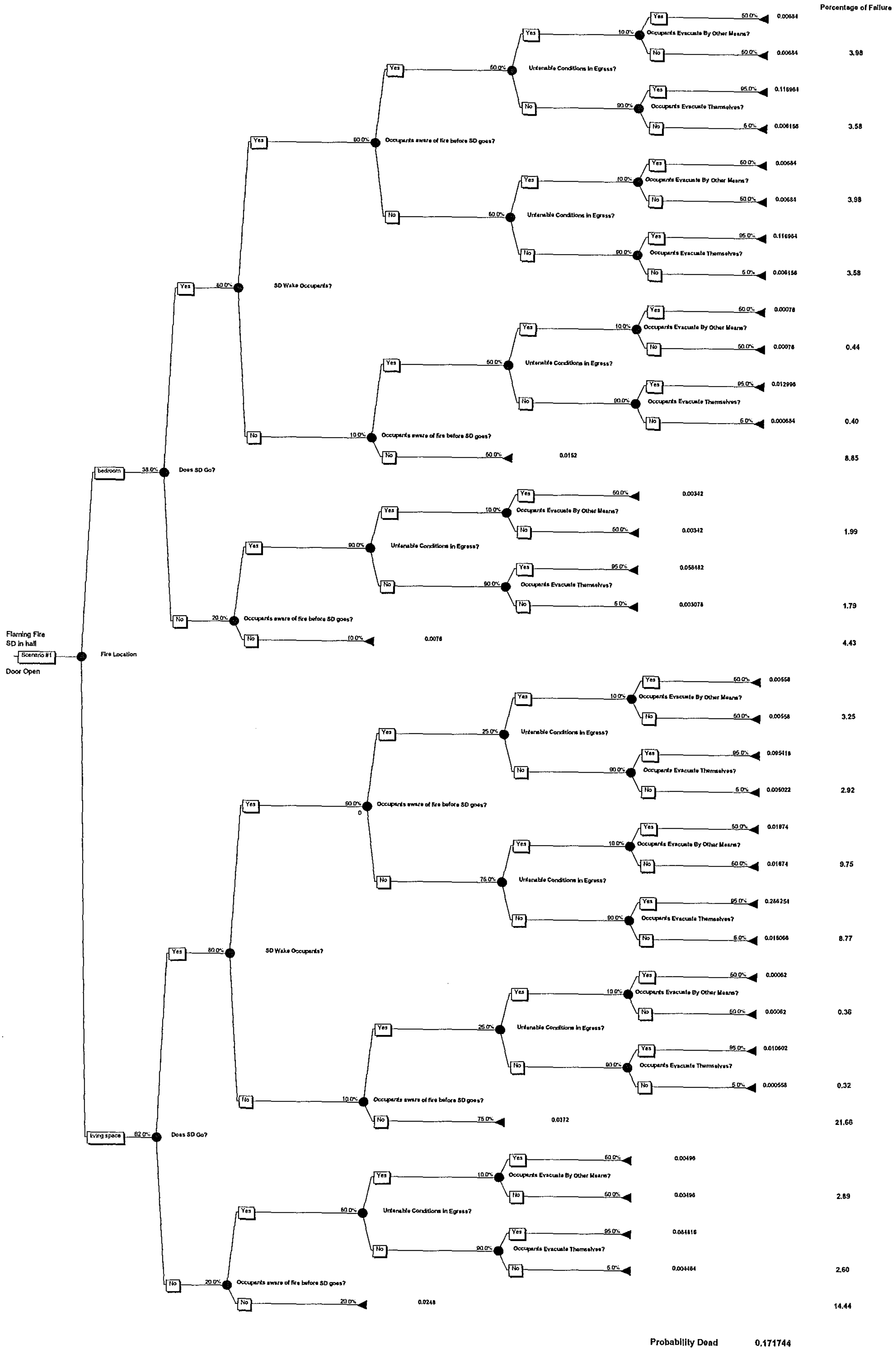
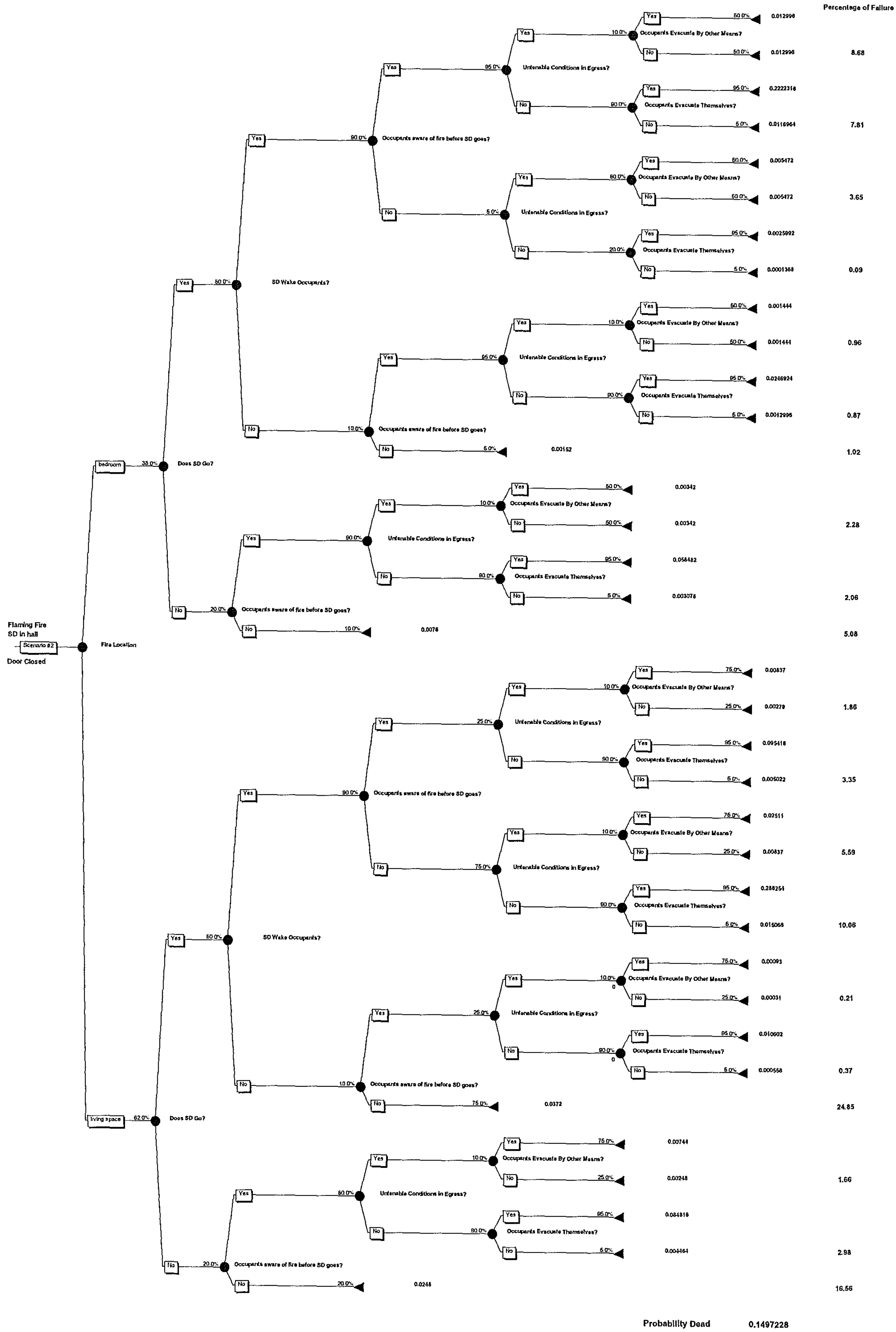
Appendix I

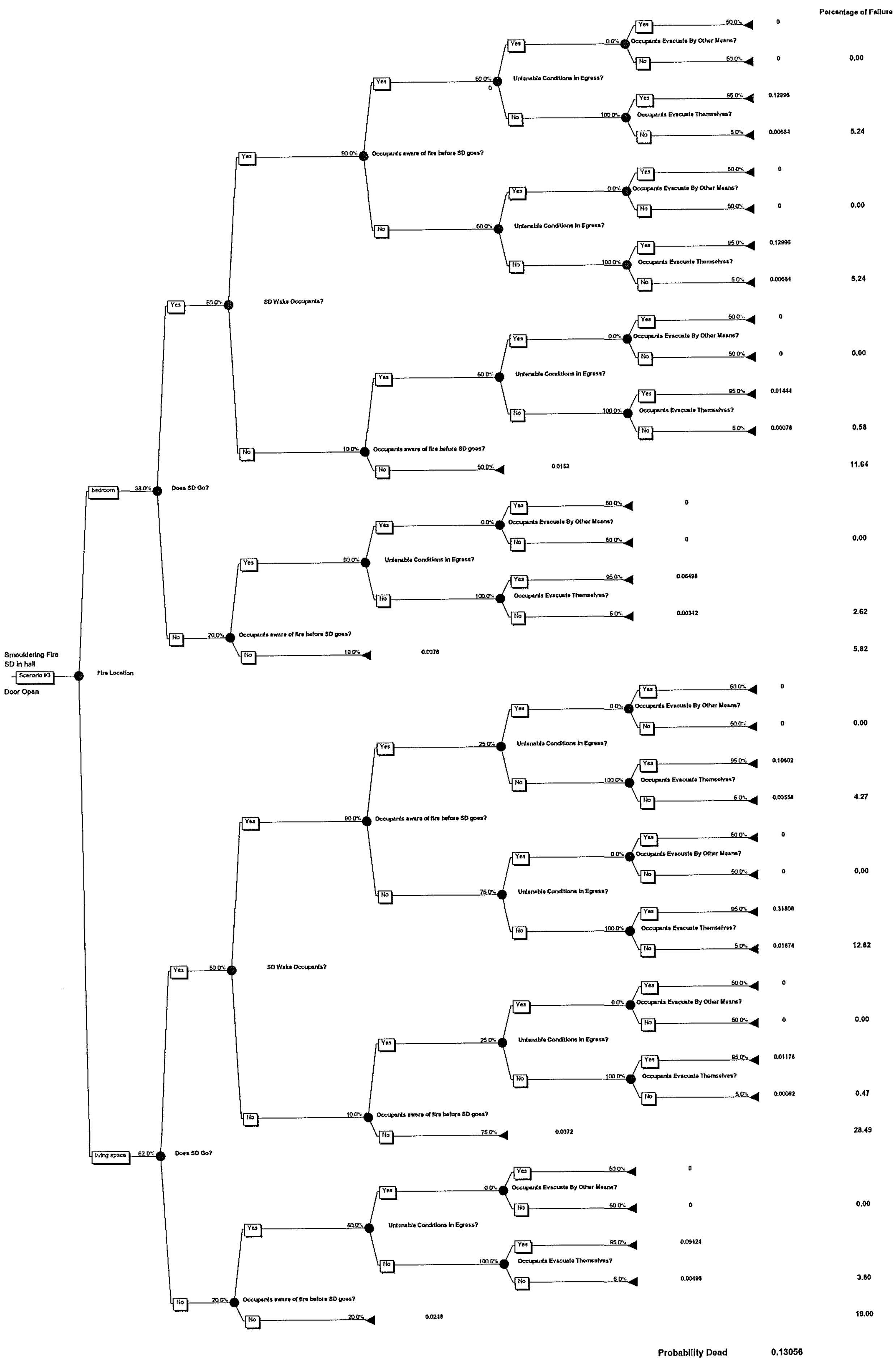
Event Trees

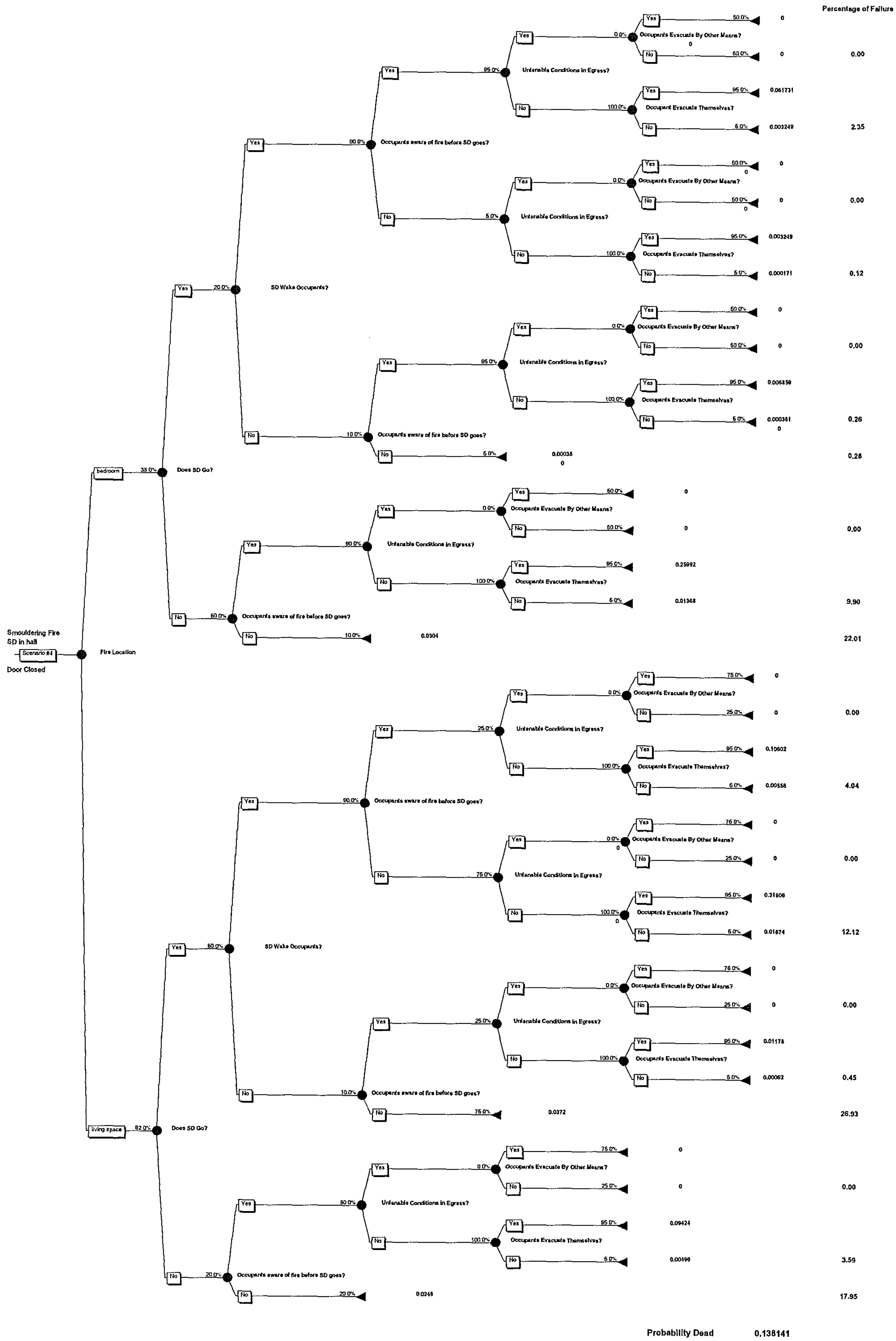
Following this page are the eight event trees used in the analysis.


Percentage of Failure
Flaming Fire
SD in hall
Scenario #1
Door Open
Fire Location
bedroom
living space
Does SD Go?
SD Wake Occupants?
Occupants aware of fire before SD goes?
Untenable Conditions in Egress?
Occupants Evacuate By Other Means?
Occupants Evacuate Themselves?
3.98
3.58
3.98
3.58
0.44
0.40
8.85
1.99
1.79
4.43
3.25
2.92
9.75
8.77
0.36
0.32
21.66
2.89
2.60
14.44
Probability Dead
0.171744

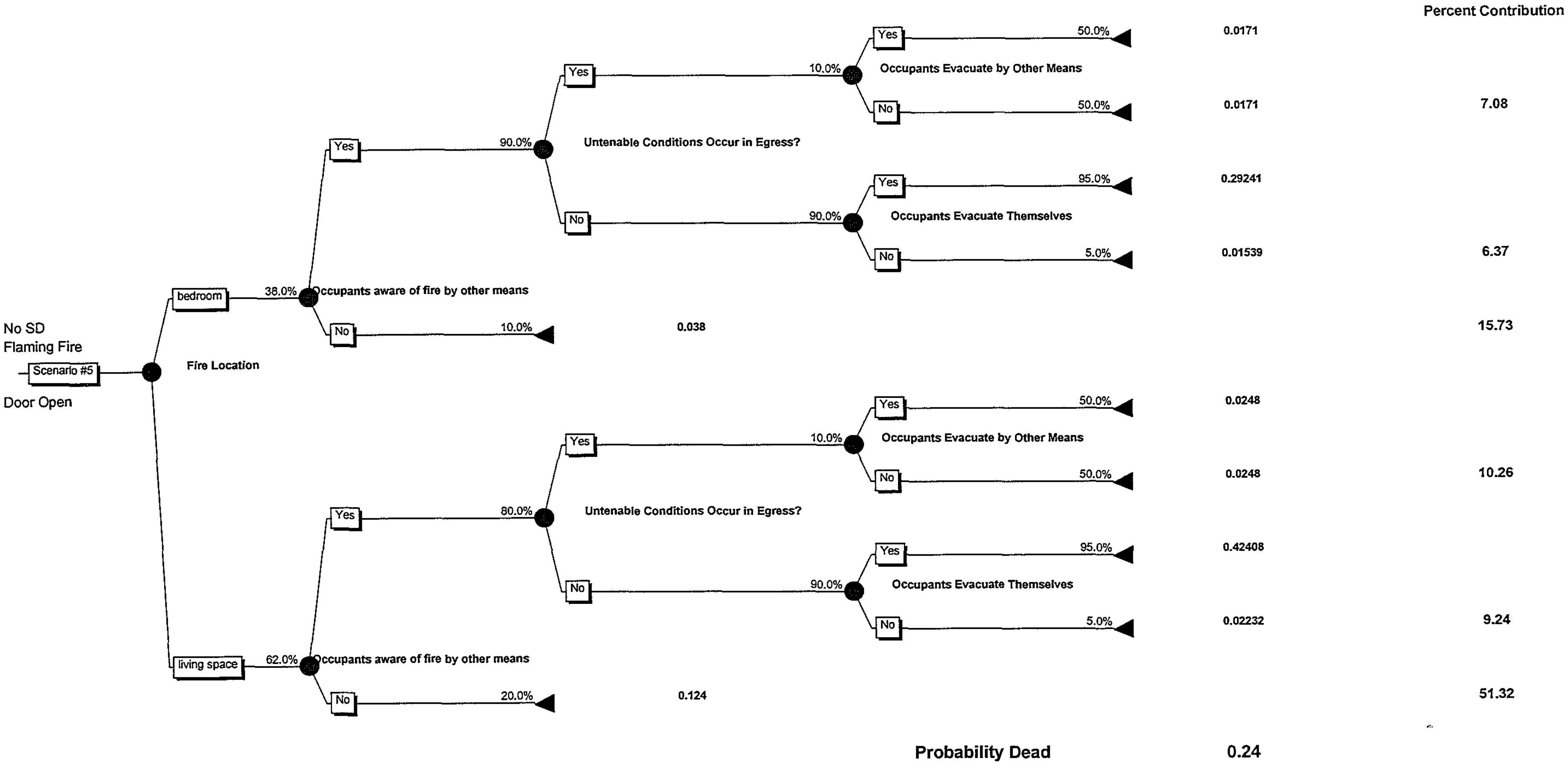


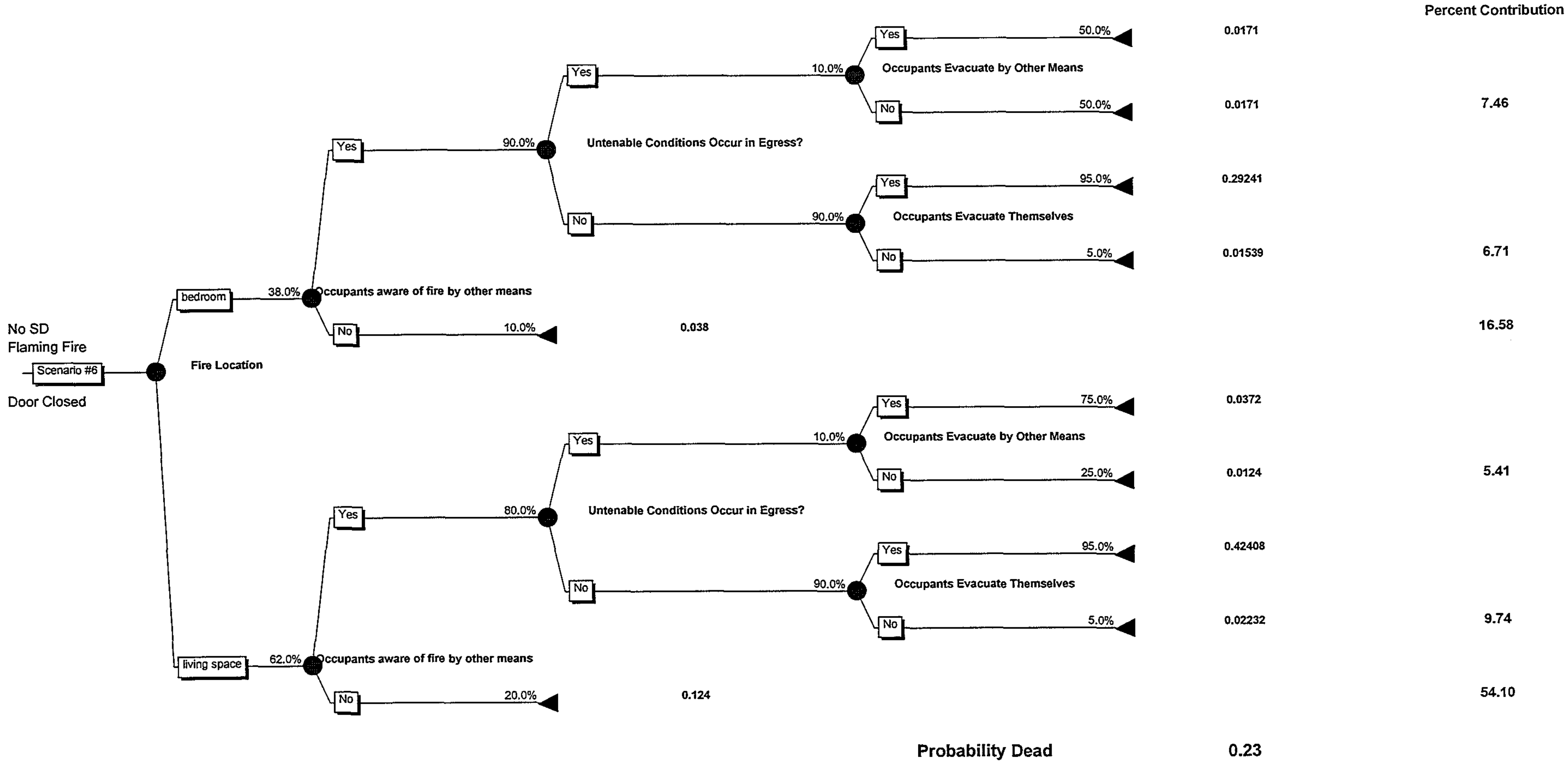
Percentage of Failure
Flaming Fire
SD in hall
Scenario #2
Door Closed
Fire Location
bedroom
living space
Does SD Go?
SD Wake Occupants?
Occupants aware of fire before SD goes?
Untenable Conditions in Egress?
Occupants Evacuate By Other Means?
Occupants Evacuate Themselves?
Probability Dead
0.1497228

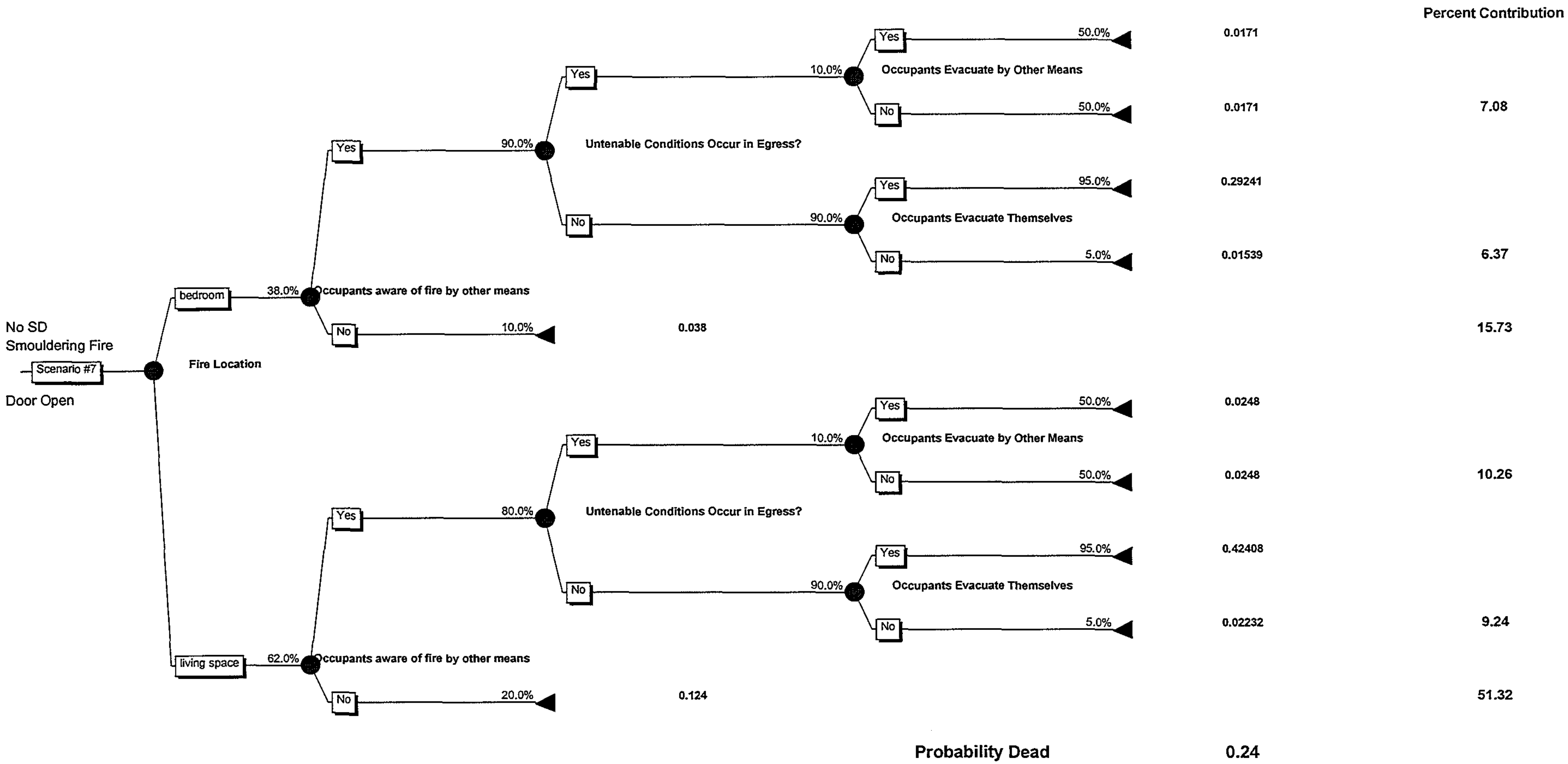

Percentage of Failure
Smouldering Fire
SD in hall
Scenario #3
Door Open
Fire Location
bedroom
living space
Does SD Go?
SD Wake Occupants?
Occupants aware of fire before SD goes?
Unfenable Conditions in Egress?
Occupants Evacuate By Other Means?
Occupants Evacuate Themselves?
0.00
5.24
0.00
5.24
0.00
0.58
11.64
0.00
2.62
5.82
0.00
4.27
0.00
12.82
0.00
0.47
28.49
0.00
3.80
19.00
Probability Dead
0.13056

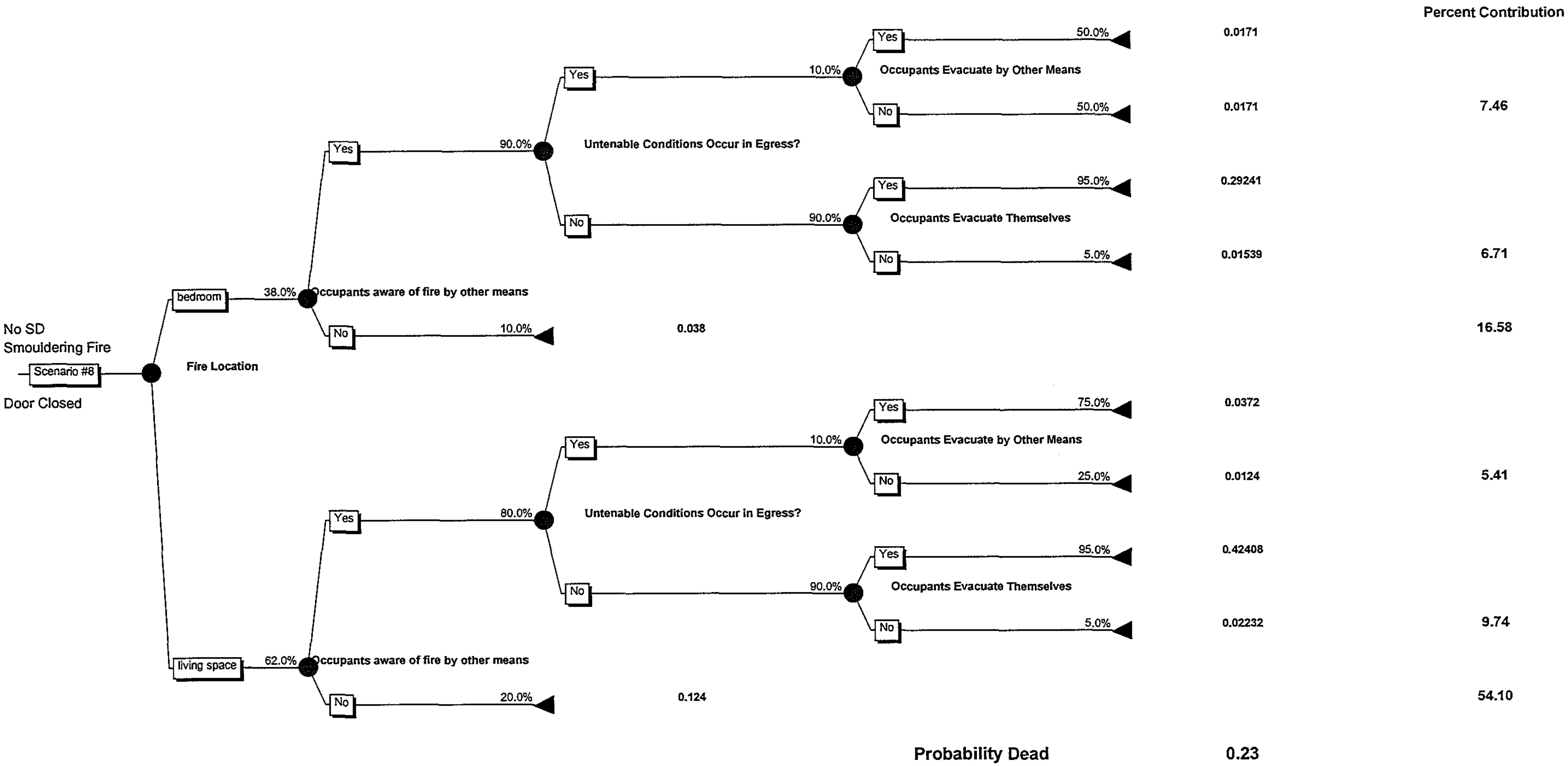


Percentage of Failure
Smouldering Fire
SD in hall
Scenario #4
Door Closed
Fire Location
bedroom
living space
Does SD Go?
SD Wake Occupants?
Occupants aware of fire before SD goes?
Unitenable Conditions in Egress?
Occupants Evacuate By Other Means?
Occupants Evacuate Themselves?
0.00
2.35
0.00
0.12
0.00
0.26
0.28
0.00
9.90
22.01
0.00
4.04
0.00
12.12
0.00
0.45
26.93
0.00
3.59
17.95
Probability Dead
0.138141


Percent Contribution
No SD
Flaming Fire
Scenario #5
Door Open
Fire Location
bedroom
38.0%
Occupants aware of fire by other means
Yes
90.0%
Untenable Conditions Occur in Egress?
Yes
10.0%
Occupants Evacuate by Other Means
Yes
50.0%
0.0171
No
50.0%
0.0171
7.08
No
90.0%
Occupants Evacuate Themselves
Yes
95.0%
0.29241
No
5.0%
0.01539
6.37
No
10.0%
0.038
15.73
living space
62.0%
Occupants aware of fire by other means
Yes
80.0%
Untenable Conditions Occur in Egress?
Yes
10.0%
Occupants Evacuate by Other Means
Yes
50.0%
0.0248
No
50.0%
0.0248
10.26
No
90.0%
Occupants Evacuate Themselves
Yes
95.0%
0.42408
No
5.0%
0.02232
9.24
No
20.0%
0.124
51.32
Probability Dead
0.24


Percent Contribution
No SD
Flaming Fire
Scenario #6
Door Closed
Fire Location
bedroom
38.0%
Occupants aware of fire by other means
Yes
90.0%
Untenable Conditions Occur in Egress?
Yes
10.0%
Occupants Evacuate by Other Means
Yes
50.0%
0.0171
No
50.0%
0.0171
7.46
No
90.0%
Occupants Evacuate Themselves
Yes
95.0%
0.29241
No
5.0%
0.01539
6.71
No
10.0%
0.038
16.58
living space
62.0%
Occupants aware of fire by other means
Yes
80.0%
Untenable Conditions Occur in Egress?
Yes
10.0%
Occupants Evacuate by Other Means
Yes
75.0%
0.0372
No
25.0%
0.0124
5.41
No
90.0%
Occupants Evacuate Themselves
Yes
95.0%
0.42408
No
5.0%
0.02232
9.74
No
20.0%
0.124
54.10
Probability Dead
0.23


Percent Contribution
No SD
Smouldering Fire
Scenario #7
Door Open
Fire Location
bedroom
38.0%
Occupants aware of fire by other means
Yes
90.0%
Untenable Conditions Occur in Egress?
Yes
10.0%
Occupants Evacuate by Other Means
Yes
50.0%
0.0171
No
50.0%
0.0171
7.08
No
90.0%
Occupants Evacuate Themselves
Yes
95.0%
0.29241
No
5.0%
0.01539
6.37
No
10.0%
0.038
15.73
living space
62.0%
Occupants aware of fire by other means
Yes
80.0%
Untenable Conditions Occur in Egress?
Yes
10.0%
Occupants Evacuate by Other Means
Yes
50.0%
0.0248
No
50.0%
0.0248
10.26
No
90.0%
Occupants Evacuate Themselves
Yes
95.0%
0.42408
No
5.0%
0.02232
9.24
No
20.0%
0.124
51.32
Probability Dead
0.24


No SD
Smouldering Fire
Scenario #8
Door Closed
Fire Location
bedroom
38.0%
Occupants aware of fire by other means
Yes
90.0%
Untenable Conditions Occur in Egress?
Yes
10.0%
Occupants Evacuate by Other Means
Yes
50.0%
0.0171
No
50.0%
0.0171
No
90.0%
Occupants Evacuate Themselves
Yes
95.0%
0.29241
No
5.0%
0.01539
No
10.0%
0.038
living space
62.0%
Occupants aware of fire by other means
Yes
80.0%
Untenable Conditions Occur in Egress?
Yes
10.0%
Occupants Evacuate by Other Means
Yes
75.0%
0.0372
No
25.0%
0.0124
No
90.0%
Occupants Evacuate Themselves
Yes
95.0%
0.42408
No
5.0%
0.02232
No
20.0%
0.124
Percent Contribution
7.46
6.71
16.58
5.41
9.74
54.10
Probability Dead
0.23

APPENDIX II

FiRECAM Input & Output

The data entered into the sixteen FiRECAM scenarios is the same apart from the following variables:

- Type of smoke alarm and its placement
- Fire Compartment Door - Open or Closed
- Non-fire Compartment Door - Open or Closed

The three variables are altered as described in Section 4.3.2, FiRECAM Scenarios. Following is a sample of the FiRECAM input for the building and building floor description and input parameters.

The expected risk to life output follows this and can be seen for all sixteen scenarios.

Scenario One

Building Description and Input Parameters

Building General Data		
City or location		Ottawa, Ontario
Date		January 19 1999 09:18:52
Selected models		FiRECAM+FDRM
File name		C:\TEMP\Debbie\FiRECAM\new5.FCI
Building indoor temperature	°C	20
Construction and Occupancy		
Occupancy group		Apartment
Building life	years	75
Building age	years	10
Building Floors		
Number of floors		1
Number of elevator shafts		0
Number of service ducts		0
Number of garbage chutes		0
Building Stairwells and Exits		
Number of ground floor exits		1
Number of stairwells used for evacuation		1
Are the stairwells exposed to outside ?		No
Width of each stairwell	m	1
Depth of each stairwell	m	1
Riser of stairs	m	0.18
Tread of stairs	m	0.28
Building Materials		
Exterior wall material		Wood Frame
Building material		Concrete
Floor material		Concrete
Stair Shaft wall material		Concrete
Interior wall material		Wood Frame
Passive Fire Resistance Ratings		
Basic building frame	min	15
Exterior walls	min	15
Fire stopping at floor	min	15
Between compartments	min	15
Compartment to corridor	min	15
Floor / Ceiling assemblies	min	15

Columns	min	15
Stair Shaft	min	15
Staircase	min	15
Service shaft	min	15
Compartment doors	min	15
Stair Shaft doors	min	15
Windows & glazing	min	15
Building Active Alarm System Type		
Alarm system type		Central Alarm
Number of alarms & min horns per floor		1
Speakers per floor		0
Voice communication		0
Direct fire department call-up		No
Manual pull bars per floor		0
Building Smoke and Heat Detectors		
Compartment smoke detectors		1
Corridor smoke detectors		0
Stair shaft smoke detectors		0
Elevator shaft smoke detectors		0
Service shaft smoke detectors		0
Garbage chute smoke detectors		0
Total number of smoke detectors in HVAC ducts (per building)		0
Compartment heat detectors		0
Corridor heat detectors		0
Stair shaft heat detectors		0
Elevator shaft heat detectors		0
Service shaft heat detectors		0
Garbage chute heat detectors		0
Total number of heat detectors in HVAC ducts (per building)		0
Building Sprinkler System		
Sprinkler system		None
Sprinkler heads per floor		0
Sprinkler system booster pumps in building		0
Flow switch & supervised valve in compartments		No
Other suppression system components (Verify Cost in Database)		No
Other type of suppression system (Verify Cost in Database)		No

Building Manual Extinguishers	
Type A extinguishers	0
Type B extinguishers	0
Type C extinguishers	0
Type ABC extinguishers	0
Private Hydrants and Fire Hoses	
Number of private fire hydrants serving building	0
Number of recessed fire hose cabinets per floor	0
Number of standpipe risers per floor	0
Number of fire department service elevators in building	0
Number of standpipe booster pumps in building	0
Elevator and Stairwell Smoke Control	
Elevator shaft pressurization	No
Stair shaft pressurization	No
Smoke exhaust fans in building	0
Smoke exhaust shafts in building	0
Evacuation and Emergency Planning	
Emergency & safety plan	No
Posted floor plans per floor	0
Emergency procedures per floor	0
Trainees for evacuation & drills per building.	0
Trainees in manual extinguishment per building.	1
Emergency telephones per floor	1
Number of emergency generators in building	0
Number of emergency light fixtures per floor	0
Number of exit signs per floor	0
Maintenance and Inspection	
Maintenance & inspection	None
Annual drills	No
Annual inspection	No
Alarm system monitoring	No

Scenario One

Building Floor Description and Input Parameters

Floor General Data		Floor 1
Floor Layout (Plan)		Rectangle
Does a Fire Start on This Floor ?		Yes
Fire Origin Compartment for This Floor		Divided Area Compartment
Does This Floor have Balconies ?		No
Floor Dimensions		
Floor Height	m	3
Floor Outer Width	m	18
Floor Outer Length	m	13
Floor Auxiliary Wing Width 1	m	3
Floor Auxiliary Wing Length 1	m	3
Floor Auxiliary Wing Width 2	m	4
Floor Auxiliary Wing Length 2	m	0
Floor Areas		
Floor Area	m2	234
Percentage of Open Floor Area	%	10
Floor Corridors		
Number of Corridors on This Floor		1
Are Horizontal Corridors Truncated at Intersections		No
Are Vertical Corridors Truncated at Intersections		No
Corridor Width	m	1.5
Total Corridor Length	m	16.2
Total Corridor Area	m2	24.3
Compartment and Walls		
Number of Compartments in Divided Area		6
Number of Columns		0
Average Wall Divider Length	m	4.86
Average Compartment Divider Length	m	6.472222
Compartment Exit Doors		
Compartment Exit Door Height	m	2.1
Compartment Exit Door Width	m	1
Windows and Balcony Glazing		
Floor Total Window Area	m2	25
Floor Total Balcony Glazing Area	m2	0
Floor Average Window Height	m	1
Floor Occupants		
Selected Floor Occupant Load		Specified Occupant Load
Total Occupants for This Floor		5
Occupants in Fire Origin Compartment		0
People In Open Areas		0
Occupant Composition		
Percentage of Male Occupants		50
Percentage of Senior and Child Occupants		50
Percentage of Disabled Occupants		5
Number of Family Groups		0

Scenario One
Expected Risk to Life

Fire Scenario Door State	Occupant State	Life Hazard	Scenario Probability	Risk to Life	% Contribution
FL/DO	Awake	2.10E-04	0.00000	0.00000	0.00
FL/DO	Asleep	1.21E-03	0.00000	0.00000	0.00
FL/DC	Awake	1.27E-04	0.24200	3.06E-05	17.71
FL/DC	Asleep	1.24E-04	0.24200	2.99E-05	17.31
NF/DO	Awake	1.97E-04	0.00000	0.00000	0.00
NF/DO	Asleep	1.94E-04	0.00000	0.00000	0.00
NF/DC	Awake	1.04E-04	0.53500	5.58E-05	32.26
NF/DC	Asleep	1.02E-04	0.53500	5.43E-05	31.43
SM/DO	Awake	5.87E-06	0.00000	0.00000	0.00
SM/DO	Asleep	4.50E-06	0.00000	0.00000	0.00
SM/DC	Awake	5.65E-06	0.22300	1.26E-06	0.73
SM/DC	Asleep	4.33E-06	0.22300	9.66E-07	0.56

Total Expected Risk to Life **0.00017** **100.00**

ERL asleep 8.53E-05

Scenario Two
Expected Risk to Life

Fire Scenario Door State	Occupant State	Life Hazard	Scenario Probability	Risk to Life	% Contribution
FL/DO	Awake	2.09E-04	0.00000	0.00000	0.00
FL/DO	Asleep	1.84E-03	0.00000	0.00000	0.00
FL/DC	Awake	1.33E-04	0.24200	3.22E-05	17.41
FL/DC	Asleep	1.27E-04	0.24200	3.06E-05	16.57
NF/DO	Awake	2.01E-04	0.00000	0.00000	0.00
NF/DO	Asleep	1.94E-04	0.00000	0.00000	0.00
NF/DC	Awake	1.12E-04	0.53500	5.97E-05	32.29
NF/DC	Asleep	1.05E-04	0.53500	5.63E-05	30.47
SM/DO	Awake	1.70E-05	0.00000	0.00000	0.00
SM/DO	Asleep	1.21E-05	0.00000	0.00000	0.00
SM/DC	Awake	1.57E-05	0.22300	3.51E-06	1.90
SM/DC	Asleep	1.12E-05	0.22300	2.49E-06	1.35

Total Expected Risk to Life **0.00018** **100.00**

ERL asleep 8.94E-05

Scenario Three
Expected Risk to Life

Fire Scenario Door State	Occupant State	Life Hazard	Scenario Probability	Risk to Life	% Contribution
FL/DO	Awake	3.91E-04	0.00000	0.00000	0.00
FL/DO	Asleep	1.85E-03	0.00000	0.00000	0.00
FL/DC	Awake	2.42E-04	0.24200	5.86E-05	13.69
FL/DC	Asleep	3.78E-04	0.24200	9.14E-05	21.37
NF/DO	Awake	3.63E-04	0.00000	0.00000	0.00
NF/DO	Asleep	5.74E-04	0.00000	0.00000	0.00
NF/DC	Awake	1.99E-04	0.53500	1.07E-04	24.94
NF/DC	Asleep	3.08E-04	0.53500	1.65E-04	38.59
SM/DO	Awake	1.64E-05	0.00000	0.00000	0.00
SM/DO	Asleep	1.22E-05	0.00000	0.00000	0.00
SM/DC	Awake	1.55E-05	0.22300	3.46E-06	0.81
SM/DC	Asleep	1.16E-05	0.22300	2.58E-06	0.60

Total Expected Risk to Life **0.00043** **100.00**

ERL Asleep 2.59E-04

Scenario Four
Expected Risk to Life

Fire Scenario Door State	Occupant State	Life Hazard	Scenario Probability	Risk to Life	% Contribution
FL/DO	Awake	3.92E-04	0.00000	0.00000	0.00
FL/DO	Asleep	1.86E-03	0.00000	0.00000	0.00
FL/DC	Awake	2.45E-04	0.24200	5.93E-05	13.53
FL/DC	Asleep	3.81E-04	0.24200	9.23E-05	21.05
NF/DO	Awake	3.65E-04	0.00000	0.00000	0.00
NF/DO	Asleep	5.76E-04	0.00000	0.00000	0.00
NF/DC	Awake	2.03E-04	0.53500	1.09E-04	24.77
NF/DC	Asleep	3.13E-04	0.53500	1.67E-04	38.17
SM/DO	Awake	3.09E-05	0.00000	0.00000	0.00
SM/DO	Asleep	2.19E-05	0.00000	0.00000	0.00
SM/DC	Awake	2.87E-05	0.22300	6.39E-06	1.46
SM/DC	Asleep	2.02E-05	0.22300	4.50E-06	1.03

Total Expected Risk to Life **0.00044** **100.00**

ERL Asleep 2.64E-04

Scenario Five

Expected Risk to Life

Fire Scenario Door State	Occupant State	Life Hazard	Scenario Probability	Risk to Life	% Contribution
FL/DO	Awake	2.10E-04	0.00000	0.00000	0.00
FL/DO	Asleep	1.21E-03	0.00000	0.00000	0.00
FL/DC	Awake	1.27E-04	0.24200	3.06E-05	17.71
FL/DC	Asleep	1.24E-04	0.24200	2.99E-05	17.31
NF/DO	Awake	1.97E-04	0.00000	0.00000	0.00
NF/DO	Asleep	1.94E-04	0.00000	0.00000	0.00
NF/DC	Awake	1.04E-04	0.53500	5.58E-05	32.26
NF/DC	Asleep	1.02E-04	0.53500	5.43E-05	31.43
SM/DO	Awake	5.87E-06	0.00000	0.00000	0.00
SM/DO	Asleep	4.50E-06	0.00000	0.00000	0.00
SM/DC	Awake	5.65E-06	0.22300	1.26E-06	0.73
SM/DC	Asleep	4.33E-06	0.22300	9.66E-07	0.56

Total Expected Risk to Life **0.00017** **100.00**

ERL Asleep 8.53E-05

Scenario Six

Expected Risk to Life

Fire Scenario Door State	Occupant State	Life Hazard	Scenario Probability	Risk to Life	% Contribution
FL/DO	Awake	2.09E-04	0.00000	0.00000	0.00
FL/DO	Asleep	1.84E-03	0.00000	0.00000	0.00
FL/DC	Awake	1.33E-04	0.24200	3.22E-05	17.41
FL/DC	Asleep	1.27E-04	0.24200	3.06E-05	16.57
NF/DO	Awake	2.01E-04	0.00000	0.00000	0.00
NF/DO	Asleep	1.94E-04	0.00000	0.00000	0.00
NF/DC	Awake	1.12E-04	0.53500	5.97E-05	32.29
NF/DC	Asleep	1.05E-04	0.53500	5.63E-05	30.47
SM/DO	Awake	1.70E-05	0.00000	0.00000	0.00
SM/DO	Asleep	1.21E-05	0.00000	0.00000	0.00
SM/DC	Awake	1.57E-05	0.22300	3.51E-06	1.90
SM/DC	Asleep	1.12E-05	0.22300	2.49E-06	1.35

Total Expected Risk to Life **0.00018** **100.00**

ERL Asleep 8.94E-05

Scenario Seven

Expected Risk to Life

Fire Scenario Door State	Occupant State	Life Hazard	Scenario Probability	Risk to Life	% Contribution
FL/DO	Awake	3.91E-04	0.00000	0.00000	0.00
FL/DO	Asleep	1.85E-03	0.00000	0.00000	0.00
FL/DC	Awake	2.42E-04	0.24200	5.86E-05	13.69
FL/DC	Asleep	3.78E-04	0.24200	9.14E-05	21.37
NF/DO	Awake	3.63E-04	0.00000	0.00000	0.00
NF/DO	Asleep	5.74E-04	0.00000	0.00000	0.00
NF/DC	Awake	1.99E-04	0.53500	1.07E-04	24.94
NF/DC	Asleep	3.08E-04	0.53500	1.65E-04	38.59
SM/DO	Awake	1.64E-05	0.00000	0.00000	0.00
SM/DO	Asleep	1.22E-05	0.00000	0.00000	0.00
SM/DC	Awake	1.55E-05	0.22300	3.46E-06	0.81
SM/DC	Asleep	1.16E-05	0.22300	2.58E-06	0.60

Total Expected Risk to Life **0.00043** **100.00**

ERL Asleep 2.59E-04

Scenario Eight

Expected Risk to Life

Fire Scenario Door State	Occupant State	Life Hazard	Scenario Probability	Risk to Life	% Contribution
FL/DO	Awake	3.92E-04	0.00000	0.00000	0.00
FL/DO	Asleep	1.86E-03	0.00000	0.00000	0.00
FL/DC	Awake	2.45E-04	0.24200	5.93E-05	13.53
FL/DC	Asleep	3.81E-04	0.24200	9.23E-05	21.05
NF/DO	Awake	3.65E-04	0.00000	0.00000	0.00
NF/DO	Asleep	5.76E-04	0.00000	0.00000	0.00
NF/DC	Awake	2.03E-04	0.53500	1.09E-04	24.77
NF/DC	Asleep	3.13E-04	0.53500	1.67E-04	38.17
SM/DO	Awake	3.09E-05	0.00000	0.00000	0.00
SM/DO	Asleep	2.19E-05	0.00000	0.00000	0.00
SM/DC	Awake	2.87E-05	0.22300	6.39E-06	1.46
SM/DC	Asleep	2.02E-05	0.22300	4.50E-06	1.03

Total Expected Risk to Life **0.00044** **100.00**

ERL Asleep 2.64E-04

Scenario Nine

Expected Risk to Life

Fire Scenario Door State	Occupant State	Life Hazard	Scenario Probability	Risk to Life	% Contribution
FL/DO	Awake	2.10E-04	0.24200	5.09E-05	9.17
FL/DO	Asleep	1.21E-03	0.24200	2.93E-04	52.75
FL/DC	Awake	1.27E-04	0.00000	0.00000	0.00
FL/DC	Asleep	1.24E-04	0.00000	0.00000	0.00
NF/DO	Awake	1.97E-04	0.53500	1.05E-04	18.99
NF/DO	Asleep	1.94E-04	0.53500	1.04E-04	18.67
NF/DC	Awake	1.04E-04	0.00000	0.00000	0.00
NF/DC	Asleep	1.02E-04	0.00000	0.00000	0.00
SM/DO	Awake	5.87E-06	0.22300	1.31E-06	0.24
SM/DO	Asleep	4.50E-06	0.22300	1.00E-06	0.18
SM/DC	Awake	5.65E-06	0.00000	0.00000	0.00
SM/DC	Asleep	4.33E-06	0.00000	0.00000	0.00

Total Expected Risk to Life **0.00056** **100.00**

ERL Asleep 3.98E-04

Scenario Ten

Expected Risk to Life

Fire Scenario Door State	Occupant State	Life Hazard	Scenario Probability	Risk to Life	% Contribution
FL/DO	Awake	2.09E-04	0.24200	5.06E-05	7.10
FL/DO	Asleep	1.84E-03	0.24200	4.45E-04	62.40
FL/DC	Awake	1.33E-04	0.00000	0.00000	0.00
FL/DC	Asleep	1.27E-04	0.00000	0.00000	0.00
NF/DO	Awake	2.01E-04	0.53500	1.07E-04	15.06
NF/DO	Asleep	1.94E-04	0.53500	1.04E-04	14.54
NF/DC	Awake	1.12E-04	0.00000	0.00000	0.00
NF/DC	Asleep	1.05E-04	0.00000	0.00000	0.00
SM/DO	Awake	1.70E-05	0.22300	3.78E-06	0.53
SM/DO	Asleep	1.21E-05	0.22300	2.70E-06	0.38
SM/DC	Awake	1.57E-05	0.00000	0.00000	0.00
SM/DC	Asleep	1.12E-05	0.00000	0.00000	0.00

Total Expected Risk to Life **0.00071** **100.00**

ERL Asleep 5.52E-04

Scenario Eleven
Expected Risk to Life

Fire Scenario Door State	Occupant State	Life Hazard	Scenario Probability	Risk to Life	% %Contribution
FL/DO	Awake	3.91E-04	0.24200	9.46E-05	9.00
FL/DO	Asleep	1.85E-03	0.24200	4.48E-04	42.65
FL/DC	Awake	2.42E-04	0.00000	0.00000	0.00
FL/DC	Asleep	3.78E-04	0.00000	0.00000	0.00
NF/DO	Awake	3.63E-04	0.53500	1.94E-04	18.50
NF/DO	Asleep	5.74E-04	0.53500	3.07E-04	29.24
NF/DC	Awake	1.99E-04	0.00000	0.00000	0.00
NF/DC	Asleep	3.08E-04	0.00000	0.00000	0.00
SM/DO	Awake	1.64E-05	0.22300	3.65E-06	0.35
SM/DO	Asleep	1.22E-05	0.22300	2.72E-06	0.26
SM/DC	Awake	1.55E-05	0.00000	0.00000	0.00
SM/DC	Asleep	1.16E-05	0.00000	0.00000	0.00

Total Expected Risk to Life 0.00105 100.00

ERL Asleep 7.58E-04

Scenario Twelve
Expected Risk to Life

Fire Scenario Door State	Occupant State	Life Hazard	Scenario Probability	Risk to Life	% Contribution
FL/DO	Awake	3.92E-04	0.24200	9.48E-05	8.95
FL/DO	Asleep	1.86E-03	0.24200	4.49E-04	42.39
FL/DC	Awake	2.45E-04	0.00000	0.00000	0.00
FL/DC	Asleep	3.81E-04	0.00000	0.00000	0.00
NF/DO	Awake	3.65E-04	0.53500	1.95E-04	18.44
NF/DO	Asleep	5.76E-04	0.53500	3.08E-04	29.11
NF/DC	Awake	2.03E-04	0.00000	0.00000	0.00
NF/DC	Asleep	3.13E-04	0.00000	0.00000	0.00
SM/DO	Awake	3.09E-05	0.22300	6.89E-06	0.65
SM/DO	Asleep	2.19E-05	0.22300	4.89E-06	0.46
SM/DC	Awake	2.87E-05	0.00000	0.00000	0.00
SM/DC	Asleep	2.02E-05	0.00000	0.00000	0.00

Total Expected Risk to Life 0.00106 100.00

ERL Asleep 7.62E-04

Scenario Thirteen
Expected Risk to Life

Fire Scenario Door State	Occupant State	Life Hazard	Scenario Probability	Risk to Life	% Contribution
FL/DO	Awake	2.10E-04	0.24200	5.09E-05	9.17
FL/DO	Asleep	1.21E-03	0.24200	2.93E-04	52.75
FL/DC	Awake	1.27E-04	0.00000	0.00000	0.00
FL/DC	Asleep	1.24E-04	0.00000	0.00000	0.00
NF/DO	Awake	1.97E-04	0.53500	1.05E-04	18.99
NF/DO	Asleep	1.94E-04	0.53500	1.04E-04	18.67
NF/DC	Awake	1.04E-04	0.00000	0.00000	0.00
NF/DC	Asleep	1.02E-04	0.00000	0.00000	0.00
SM/DO	Awake	5.87E-06	0.22300	1.31E-06	0.24
SM/DO	Asleep	4.50E-06	0.22300	1.00E-06	0.18
SM/DC	Awake	5.65E-06	0.00000	0.00000	0.00
SM/DC	Asleep	4.33E-06	0.00000	0.00000	0.00

Total Expected Risk to Life **0.00056** **100.00**

ERL Asleep 3.98E-04

Scenario Fourteen
Expected Risk to Life

Fire Scenario Door State	Occupant State	Life Hazard	Scenario Probability	Risk to Life	% Contribution
FL/DO	Awake	2.09E-04	0.24200	5.06E-05	7.10
FL/DO	Asleep	1.84E-03	0.24200	4.45E-04	62.40
FL/DC	Awake	1.33E-04	0.00000	0.00000	0.00
FL/DC	Asleep	1.27E-04	0.00000	0.00000	0.00
NF/DO	Awake	2.01E-04	0.53500	1.07E-04	15.06
NF/DO	Asleep	1.94E-04	0.53500	1.04E-04	14.54
NF/DC	Awake	1.12E-04	0.00000	0.00000	0.00
NF/DC	Asleep	1.05E-04	0.00000	0.00000	0.00
SM/DO	Awake	1.70E-05	0.22300	3.78E-06	0.53
SM/DO	Asleep	1.21E-05	0.22300	2.70E-06	0.38
SM/DC	Awake	1.57E-05	0.00000	0.00000	0.00
SM/DC	Asleep	1.12E-05	0.00000	0.00000	0.00

Total Expected Risk to Life **0.00071** **100.00**

ERL Asleep 5.52E-04

Scenario Fifteen

Expected Risk to Life

Fire Scenario Door State	Occupant State	Life Hazard	Scenario Probability	Risk to Life	% Contribution
FL/DO	Awake	3.91E-04	0.24200	9.46E-05	9.00
FL/DO	Asleep	1.85E-03	0.24200	4.48E-04	42.65
FL/DC	Awake	2.42E-04	0.00000	0.00000	0.00
FL/DC	Asleep	3.78E-04	0.00000	0.00000	0.00
NF/DO	Awake	3.63E-04	0.53500	1.94E-04	18.50
NF/DO	Asleep	5.74E-04	0.53500	3.07E-04	29.24
NF/DC	Awake	1.99E-04	0.00000	0.00000	0.00
NF/DC	Asleep	3.08E-04	0.00000	0.00000	0.00
SM/DO	Awake	1.64E-05	0.22300	3.65E-06	0.35
SM/DO	Asleep	1.22E-05	0.22300	2.72E-06	0.26
SM/DC	Awake	1.55E-05	0.00000	0.00000	0.00
SM/DC	Asleep	1.16E-05	0.00000	0.00000	0.00

Total Expected Risk to Life **0.00105** **100.00**

ERL Asleep **7.58E-04**

Scenario Sixteen

Expected Risk to Life

Fire Scenario Door State	Occupant State	Life Hazard	Scenario Probability	Risk to Life	% Contribution
FL/DO	Awake	3.92E-04	0.24200	9.48E-05	8.95
FL/DO	Asleep	1.86E-03	0.24200	4.49E-04	42.39
FL/DC	Awake	2.45E-04	0.00000	0.00000	0.00
FL/DC	Asleep	3.81E-04	0.00000	0.00000	0.00
NF/DO	Awake	3.65E-04	0.53500	1.95E-04	18.44
NF/DO	Asleep	5.76E-04	0.53500	3.08E-04	29.11
NF/DC	Awake	2.03E-04	0.00000	0.00000	0.00
NF/DC	Asleep	3.13E-04	0.00000	0.00000	0.00
SM/DO	Awake	3.09E-05	0.22300	6.89E-06	0.65
SM/DO	Asleep	2.19E-05	0.22300	4.89E-06	0.46
SM/DC	Awake	2.87E-05	0.00000	0.00000	0.00
SM/DC	Asleep	2.02E-05	0.00000	0.00000	0.00

Total Expected Risk to Life **0.00106** **100.00**

ERL Asleep **7.62E-04**

APPENDIX III

FAST Input and Output

FAST was used to find species concentrations of the smoke in the hallway or bedroom (egress route) for fires starting either in the living area or bedroom. A typical house was modelled with three compartments joined together by horizontal vents. The sizes of the compartments were determined by looking at house plans that were given by various housing experts, the room sizes used in the modelling are as follows:

- Bedroom 3m x 4m
- Hallway 1m x 5m
- Living Area 5m x 4m

The horizontal vents between compartments model the position of the door. If the door was open then a vent 2.1m X 1m was modelled and when the door was closed a very thin, tall vent was used. The fire modelled was a fast growing flaming fire starting in either the bedroom or the living area. To determine species concentrations it is necessary to input the hydrogen to carbon ratio, and the carbon and carbon monoxide to carbon dioxide ratios for the material that is burning. Polyurethane foam data was used for these ratios because it is likely that fires will start on couches, beds or other materials contained foam. The data for polyurethane foam is sourced from Table 3-4.11, Section 3, Chapter 4 of the SFPE Fire Protection Engineering Handbook (1995).

The species concentration output gained from FAST was used to define the times for untenability and smoke alarm activation. The following two sections, untenability and smoke alarm activation, detail the methods used once data from FAST was determined.

Untenability Information

The species concentration data used for untenability calculations were determined by modelling on FAST. The species concentrations, in the upper layer of the compartments, used were carbon monoxide, carbon dioxide and oxygen. The method used to determine untenability is the Fractional Incapacitating Dose method (FID) described by Purser (1995). The fractional incapacitating dose is determined using the interaction between carbon monoxide and carbon dioxide. When the fractional incapacitating dose reaches unity the occupants die. Because the time to untenability in the egress is required, a lower value of 0.25 for the FID is used as the untenability criteria. This lower value is used for conservatism. The difference in time to untenability between using unity and 0.25 is very small and does not affect the probability of untenability. The calculations used and explanations by Purser can be seen in Section two, Chapter eight in the SFPE Fire Protection Handbook(1995). The results of the times to untenability for the scenarios are shown in Section 5.1.1 of this report. The equations used to determine the times to untenability are shown below and are calculated at each time interval of ten seconds.

$$F_{ICO} = \frac{8.2925x10^{-4}(CO(ppm))^{1.036}}{30}$$ Equation III.1

where F_{ICO} is the fraction of incapacitating dose for CO

$$F_{ICO_2} = \frac{1}{\exp(6.1623-(0.5189(CO_2(ppm)))}$$ Equation III.2

where F_{ICO2} is the fraction of incapacitating dose for CO_2.

$$VCO_2 = \frac{\exp(0.1903 * CO_2(ppm) + 2.0004}{7.1}$$ Equation III.3

where VCO_2 is the multiplication factor for CO_2-induced hyperventilation

$$F_{IO} = \frac{1}{\exp(8.13 - 0.54(20.9 - O_2(ppm))}$$ Equation III.4

where F_{IO} is the fraction of incapacitating dose of low-oxygen hypoxia

The above four calculations are used in the final equation that calculates the fraction of an incapacitating dose of all the narcotic gases used F_{IN}.

$$F_{IN} = [F_{ICO} * VCO_2 + F_{IO}] \text{ or } F_{ICO2}$$ Equation III.5

When F_{IN} reaches the value of 0.25 in the compartment of interest then the corresponding time is the time at which conditions have become untenable.

Smoke Alarm Activation

It is very easy to determine the time when the smoke alarm activated for flaming fires when there are no obstructions such as walls or doors between the fire and the smoke alarm. The detector response program from FPETOOL is used with distances from the fire to the smoke alarm depending on where the fire location is. A moderate fire growth rate is used for conservatism. The results for the scenarios where the door is open for flaming fires can be seen in Section 5.1.1 of this report.

For smouldering fires or for fires where there is a closed door between the fire and the alarm the method by Mulholland is used to determine times to smoke alarm activation. The method by Mulholland is found in the SFPE Fire Protection Engineering Handbook(1995), Section two, Chapter 15. The method determines the time for the smoke alarm to activate by using the electrical output of the smoke alarm represented by the size distribution of the smoke and the response function of the alarm. The alarm point of the smoke alarm is defined as a voltage when the alarm will activate from a certain amount and type of smoke. Because of these alarm conditions it is important to specify the burning rate of the object correctly as well as the properties of the smoke that it produces. An article by Quintere *et. al.*(1982) defines the burning rate of polyurethane and cotton to be approximately linear up until the time the fuel limit is reached. The burning rate, determined by experimentation, is given by the following equation:

$$m = ct \quad [g/min] \quad \text{where } c = 0.206\ g/min^2 \qquad \text{equation III.6}$$

Smoke properties for smouldering fires such as the smoke conversion factor (the mass of smoke produced per mass of fuel burned), the size distribution of the smoke and the geometric standard deviation have been determined from tables in the chapter by Mulholland in the SFPE Fire Protection Engineering Handbook(1995). For flaming fires, the species concentrations determined by FAST modelling are used instead of the tables to determine the type and amount of smoke produced. The following table, Table III.1 shows the data used in the Mulholland method for smouldering fires.

Table III.1 Data used in Mulholland method (from SFPE(1995) Section 2 Chapter 15)

Variable	Symbol and Units	Value
Smoke Conversion Factor	ε (mass of smoke produced/ mass of fuel burned	0.03
Volume surface mean diameter	d_{32} (μm)	0.75
Geometric standard deviation	σ_g	2.0
Number concentration	c (μV per particle concentration per μm)	7
Density	ρ (g/cm^3)	2

The volume of the room in consideration is required so that the concentration of the smoke can be determined in the space. If the door is open between the hallway and the bedroom then the entire volume of the two areas are used. If the bedroom door is closed then only the volume of the hallway or the bedroom is used depending on the location of the fire. There is no closed door between the living area and the hallway. The times of the smoke alarm activation for all the scenarios can be seen in the results Section, 5.1.1. The equations used to determine the time that the smoke alarm activates, as described by Mulholland in the SFPE Fire Protection Engineering Handbook(1995) follow.

$$d_{gn} = d_{32} \exp\left(-\frac{5}{2}\ln^2 \sigma_g\right) \qquad \text{equation III.7}$$

where d_{gn} is the geometric number diameter measured in μm.

$$m = \frac{1}{6}\pi\rho N_O d_{gn}^3 \exp\left(\frac{3}{2}\ln^2 \sigma_g\right) \qquad \text{equation III.8}$$

where m is the mass concentration of the smoke and is the third moment of the size distribution. The variable m [g/cm^3] can be determined by finding the amount of smoke produced, which is determined by knowing the burning rate and the mass of smoke produced per mass of fuel burned, and dividing it by the volume of the room.

Once m is known, it is used in equation III.8 to find N_O which is used in equation III.9 to find P, the alarm output measured in Volts.

$$P = cN_O d_{gn} \exp\left(\frac{1}{2}\ln^2 \sigma_g\right) \qquad \text{equation III.9}$$

When P reaches the alarm point of 2.5V, the alarm activates, this is the time used in the analysis to find the probability of untenability.

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